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DTNSRDC-83/054

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

REMARKS ON SHIP MODEL TESTING, FACILITIES, AND TEST RESULTS

THE EIGHTH DAVID W. TAYLOR LECTURES

by

Hans Edstrand

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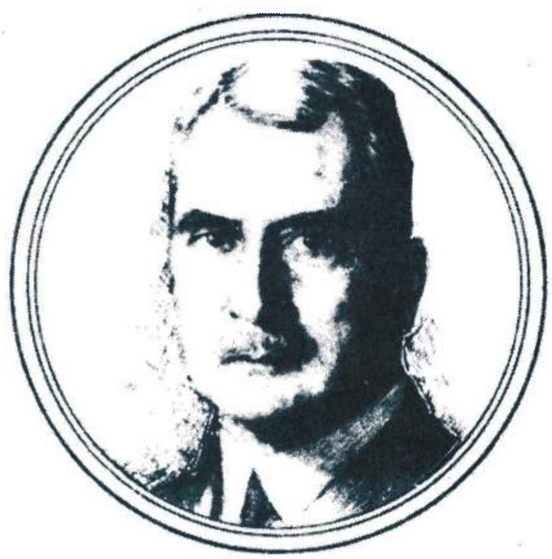

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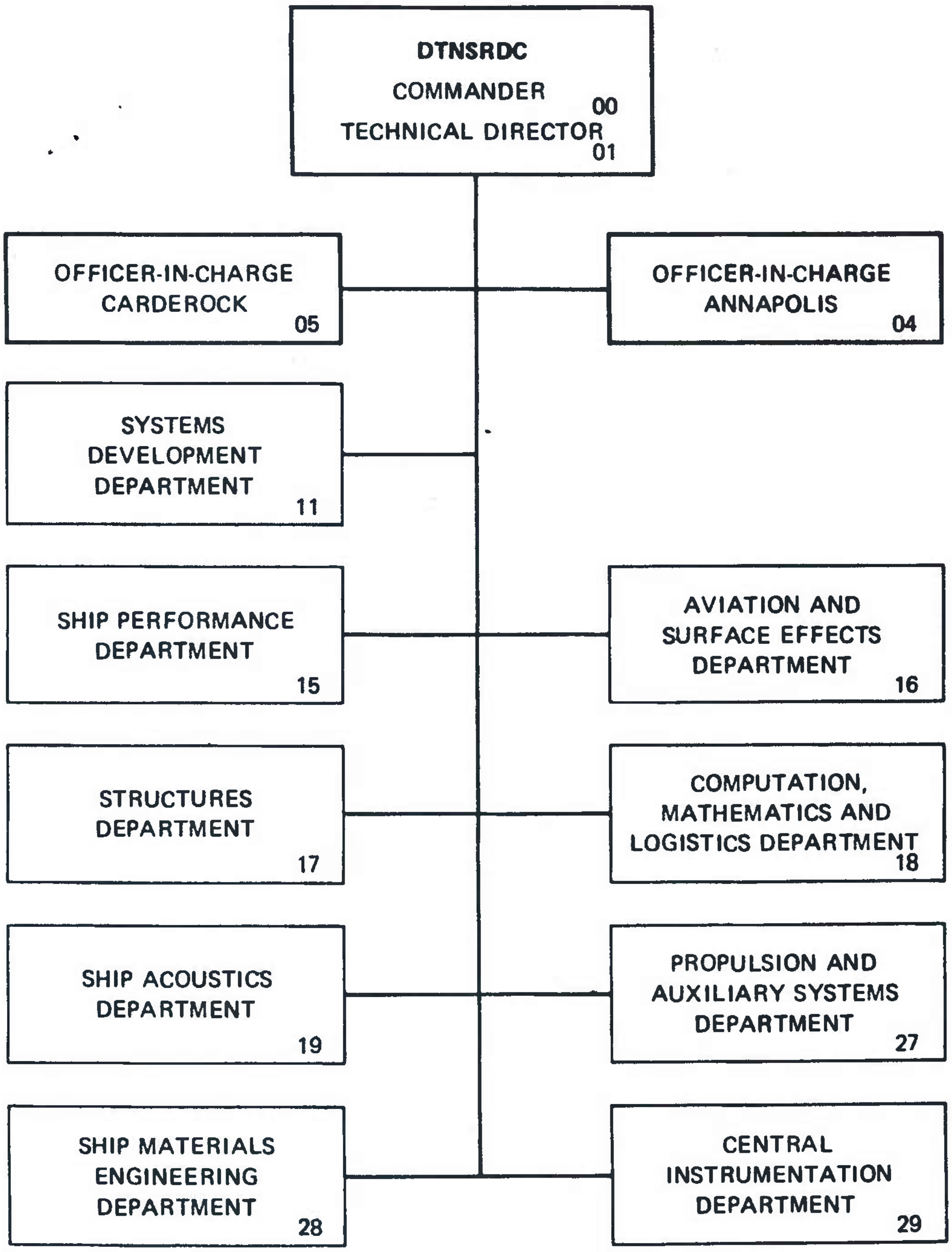

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER DTNSRDC-83/054	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) REMARKS ON SHIP MODEL TESTING, FACILITIES, AND TEST RESULTS		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Hans Edstrand		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 4-1500-001-43
11. CONTROLLING OFFICE NAME AND ADDRESS David W. Taylor Naval Ship Research and Development Center Bethesda, Maryland 20084		12. REPORT DATE February 1984
		13. NUMBER OF PAGES 97
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		
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PREFACE

The David W. Taylor Lectures were conceived to honor our founder in recognition of his many contributions to naval architecture and naval hydromechanics. Previous lecturers in this series have presented material that reminds us of the more theoretical aspects of Admiral Taylor's career. But it should never be forgotten that his primary purpose in building the Experimental Towing Tank and its associated facilities was to solve the hydrodynamic problems facing the ship designer. He was himself involved in the development of many ship designs for the U.S. Navy, and was a major leader in the translation of towing tank observations into ship design decisions. Dr. Hans Edstrand, recently retired Director General of the Swedish Maritime Research Centre, (SSPA), was invited to give a series of lectures that would reflect this aspect of Admiral Taylor's work. Dr. Edstrand is himself a pioneer in the development of model testing facilities. The variable pressure tunnel, which was built at SSPA under his guidance, is a powerful and unique facility. He led his organization to its current recognition as one of the world's finest ship research laboratories. He has always insisted that his theoretically inclined colleagues give more attention to the fundamental problem of designing better ships.

LECTURE I

SHIP MODEL TESTING RESEARCH, A HISTORY

INTRODUCTION

This chapter is not intended to give a comprehensive history of ship model testing and International Towing Tank Conferences, but rather to present some personal comments on these subjects.

For a long time, model tests have been used to determine the resistance from the surrounding fluid as a body is moved through water. We do not really know when such tests were first used. In the Bible, the main dimensions of Noah's Ark are given. They agree surprisingly well with present day opinion concerning proportions of main dimensions. However, it is, of course, unlikely that Noah carried out ship model investigations.

In Great Britain the interest in ship model testing awoke early, in connection with naval ship design and construction during the Napleonic wars. Beaufoy, for instance, carried out model experiments around 1790 in Greenland Dock in London. The ship models were towed by falling weights, a method common at the time.

A concrete example of how at this time results from ship model testing influenced ship design development are the famous Tea Clippers. Around 1830 the Scottish firm Alexander Hall of Aberdeen carried out model tests for this type of ship. The towing tank had a length of only 10 ft, the breadth was 12 in., and the depth 16 in. The tank was filled with 10 in. of water. Over the water was a layer of red paint, 1 1/2 in. thick. The models were towed with a string passing over a drum and carrying a falling weight. By using the same weight on different model configurations the relative speeds could be measured and thus the quality of the different configurations could be judged. The movement of the red paint around the hull allowed the flow pattern on different models to be observed.

In France early interest was concentrated on problems concerning ships in canals and shallow waters. Around 1770 d'Alembert was commissioned by the French Academy to investigate these problems. A towing tank was built for this purpose. It had the dimensions 32.5 × 17.2 × 2.1 m.

The earliest known proposal for the use of towed models for the investigation of ship resistance may be that of the Swede Kristoffer Polhem. In a paper "Om Skieppens fart i sjön" ("Concerning ships' speed at sea")[1*] he recommended in 1717 to the Royal Swedish Scientific Academy that ship model tests be carried out. Other Swedes who shared Polhem's interest in ship model testing were Swedenborg, Sheldon, and Chapman. Fredrik Henrik af Chapman is the first Swede known to have carried out ship model investigations.

Chapman, who was of a Scottish family that had settled in Sweden, became Admiral of the Swedish Navy and was responsible for the Swedish Naval Shipyard at Karlskrona in the south of Sweden. Around 1760, Chapman arranged a towing tank with ship models towed by falling weights at his farm, Skärva, outside Karlskrona. The dimensions of the tank were 68 × 15 × 4 ft. Some of his ship models are said to have been made with oiled paper stretched over wooden frames. Parts of an old stone foundation, still visible at Skärva, are said to be the remains of "Chapman's Laboratory." In 1794, at the age of 73, he tested logs with systematically varied angles of entrance and runs in his tank.

WILLIAM FROUDE

A common trait of all these pioneers is that they understood the usefulness and necessity of ship model tests, but that they could not transform the model test results to ship scale. The model laws were unknown to them.

It was the Englishman William Froude who in 1869 formulated his "Law of Comparison," stating the conditions under which model tests could be used to predict full-scale resistance. The same law had previously been set down by a Frenchman, Reech, in 1844, but he had not demonstrated how it could be applied to the practical problem of predicting ship resistance. That practical application was left to William Froude, and he is therefore called the father of modern ship model testing.

William Froude, who was a civil engineer, had done ship model experiments as early as in 1862. He used the gravity towing method, where a falling weight on a string over a pulley towed the model.

*Superscript numbers refer to references at the end of the report.

In 1870 the British Admiralty commissioned Froude to build an experiment tank. The tank was built at Torquay in Devon, England, in 1871. It was the first establishment with a towing carriage spanning the tank. The main dimensions were 2.78 × 36 × 10 ft. Models with lengths up to 12 ft were used. At this time William Froude was already 61 years old. The funds provided by the Admiralty were very small--£1 000 to build the tank and £1 000 to run it for 2 years. Froude's own service was given free.

The towing tank at Torquay was the first experiment tank (model basin) with a traveling carriage of the kind we know so many of today. The tank was built for set purposes and was closed down after a few years. The site has since been used for other purposes. In 1954, 75 years after Froude's death, a memorial tablet was unveiled at the place where his tank had been. The following words can be read on the tablet:

> William Froude was born in 1810 at Dartington, Devon, and lived at Chelston Cross from 1867, until his death in 1879. His outstanding contributions to the science of naval architecture brought him worldwide renown. He was the pioneer of ship model research and in 1872 built the first experiment tank in the world on this site for the Admiralty for whom his main work was carried out.
>
> This memorial was erected in 1954 by naval architects of many countries as a grateful tribute to his genius.

DEVELOPMENTS SINCE FROUDE

The second experiment tank after that of William Froude was built by B.J. Tideman for the Royal Dutch Navy in the Naval Yard in Amsterdam in 1873. It was built without a roof and was used up to the close of the century for tests on Dutch naval and merchant vessels. The third tank was the first one initiated by a private shipbuilding firm for its own use to solve design problems. It was built in 1884 by William Denny at Dumbarton, Scotland. It is still in use, although the original owner-firm no longer exists.

Froude's tank at Torquay must have been considered useful, because the British Admiralty decided to build a new and larger one in 1886. This tank was constructed at Haslar, near Portsmouth, under the direction of R.E. Froude, William's son. Its dimensions are 400 × 20 × 9 ft.

Towing tanks were subsequently built in Italy (Spezia), Russia (St. Petersburg) and Germany (Dresden). The first towing tank in the United States was built in the Navy Yard in Washington, D.C., in 1900.

From 1900 on many new ship towing tanks were established. Germany built one in Bremerhaven in 1900 and another at the Technical University, Charlottenburg, in 1902. The French Government built one near Paris in 1905 and the same year the tank at Michigan University, Ann Arbor, was inaugurated. In 1908 the Clydebank Tank was built. Here many models of large and fast Atlantic liners have been tested.

The first Japanese tank was built in Nagasaki in 1908. Two years later another tank was built in Tokyo. The first towing tank at the National Physical Laboratory in the United Kingdom was opened in 1911. A very large tank was completed in Hamburg during World War I in 1915 and a smaller one in Vienna in 1916. In Italy, a second tank in addition to the one in Spezia was built in Rome and opened in 1929. A new large tank was constructed at Haslar (British Admiralty) in 1932 and the same year the Wageningen Tank in Holland was completed.

In Sweden the first small towing tank was built in 1921. It was connected with the Royal Technical University in Stockholm and was for almost 20 years the only tank in Scandinavia. Its dimensions are 60 × 3 × 1.35 m. The towing carriage has a maximum speed of 3.85 m/s. In connection with the expansion in Swedish shipbuilding, and as a result of the needs of the Swedish Navy, a large modern ship towing tank was considered necessary. This establishment, SSPA, was located in Gothenburg and opened in 1940.

It is impossible for me to enumerate all the ship towing tanks and similar establishments which have been built during the last 40 or 50 years. I personally believe there are too many. National prestige, fear of competition, other reasons have forced nations and firms to over-establish in this field. The enormous investments are not giving the return that they ought to.

Of course, over the years, the design of the ship model towing tank as it was constructed by William Froude at Torquay has been improved and changed as new tanks have been built. The main dimensions are often very much larger, the speed of the measuring carriages has been increased, the measuring devices and methods have become more sophisticated.

Most ship model towing tanks nowadays are supplemented with other means for ship model investigations. Thus an establishment of this type very often has different towing tanks for different purposes, for instance a special tank for shallow water tests, a high speed towing tank, a laboratory for seakeeping and maneuverability tests, and so on. Many establishments have one or more cavitation tunnels or circulating water tunnels. In at least two places--the Leningrad tank in Russia and the Wageningen tank in the Netherlands--vacuum towing tanks are in operation, so as to combine cavitation investigations with the traditional towing tests. Ice laboratories are operating at several establishments to allow the investigation of resistance and other conditions in ice.

Maybe it should be mentioned that many establishments have only one or a few of these various facilities. Very often, for example, a propeller firm or a university has built only a cavitation tunnel for ship propeller investigations or research.

INTERNATIONAL TOWING TANK CONFERENCES, A HISTORY

DIE KONFERENZ ÜBER HYDROMECHANISCHE PROBLEME DES SCHIFFSANTRIEBS, HAMBURG, 1932

In May 1932 an International Hydromechanical Conference took place in Hamburg. This Conference was initiated and organized by the German Towing Tank in Hamburg (Die Hamburgische Schiffbau-Versuchsanstalt) and a Society associated with this institution (Die Freunde und Förderer der Hamburgischen Schiffbau-Versuchsanstalt). Hosts were Dr. Ing. G. Kempf and Dr. Ing. E. Foerster. Dr. Kempf was at that time Director of the Hamburg Towing Tank.

The Proceedings[2] of the Conference were published in 1932: "Hydromechanische Probleme des Schiffsantriebs." Dr. Karl E. Schoenherr from the United States and the Experimental Model Basin, Navy Yard, Washington, D.C. gave the paper: "The

Influence of Temperature on the Frictional Resistance Experienced by Plane Surfaces Moving in a Fluid." Many other scientists from various towing tanks and professors from universities in Europe presented interesting papers. Particularly the twelve papers within the field of cavitation are looked upon today, at least in Europe, as more or less classical.

INTERNATIONAL CONFERENCE OF TANK SUPERINTENDENTS

In an after-dinner speech during the Conference in Hamburg one of the delegates, Mr. John de Meo, pleaded strongly for international technical cooperation in the field of ship propulsion. Several towing tank superintendents taking part in the Hamburg Conference were in favour of de Meo's idea and wanted to continue as outlined in Hamburg. One of them, the director of the Wageningen Tank in the Netherlands, Professor L. Troost, took the initiative and invited his colleagues who were present in Hamburg to come to the Netherlands in 1933 to discuss what form the cooperation among the tanks should take.

Thus the first International Conference of Tank Superintendents (this was the name of the ITTC at that time) took place in the Hague, the Netherlands, July 13th and 14th 1933. It was attended by 23 delegates.

There are and always have been people within our profession who want to regard the Hamburg Conference in 1932 as the first. In the Preface to the Proceedings[3] of the Conference in the Hague Professor Troost says the following:

> The Council of the Dutch Experimental Tank in Wageningen issued an invitation to all experimental tank superintendents and some other specialists for a Conference to be held in the Hague, on 13th and 14th July 1933.
>
> This meeting took place and is to be regarded as a first step towards reaching a standard system of publication of tank results.

The discussions, which were informal and confidential, led to the appointment of a Committee of four (Baker, Barrillon, Kempf, Troost) to work out the general conclusions in a more definite way. (Thus apparently already at the first Conference a Technical Committee was necessary in order to sum up all different opinions.)

Further, Troost states that the intention of the Conference, which was to give the tank officials an opportunity of conferring in an open and confidential manner on their own methods and also on the manner of publication of tank results, had been fully realized.

Troost sums up in his Preface by saying that international cooperation in the field of tank research work for ship propulsion was in progress and that the pioneer work of Mr. de Meo, who long had been advocating international technical coordination on general lines, did not seem to have been in vain as far as tank work was concerned.

Before World War II three further conferences were held. In London in 1934 in connection with the Summer Meetings of the Institution of Naval Architects, in Paris in 1935, and in Berlin in 1937. A conference was planned for Rome in 1939 but was cancelled.

The first International Conference of Ship Tank Superintendents after the War took place in London in 1948 at the invitation of the British tanks. Since then a conference has been held every third year in various countries. The latest one, the 16th, was held in Leningrad, USSR, in August and September 1981. The next one will be held in Gothenburg, Sweden, in September 1984.

The Conference has grown steadily; in Leningrad there were about 220 delegates and observers from 30 countries. The organizing work is carried out in an Executive Committee and the technical work in Technical Committees, today numbering nine. A set of Rules of Organization is applied. The present set was adopted by the 13th Conference in 1972 in Berlin and Hamburg.

INTERNATIONAL TOWING TANK CONFERENCE (ITTC)

Among the scientific and technical achievements of the conferences only a few will be mentioned here. In 1935 in Paris the formula for calculating friction resistance was agreed upon. In Madrid the ITTC 1957 model-ship correlation line was adopted. In 1978 in the Hague the ITTC member organizations were recommended to use the 1978 ITTC Performance Prediction Method for Single Screw Ships.

For some reason the ITTC has always been very popular. The demand for invitations for delegates increases all the time. Not only professionals in tankery, but university professors, consultants, and shipbuilders' and shipowners' representatives have shown considerable interest.

My predecessor as Director General of SSPA, Dr. H.F. Nordström, was of the opinion that the Conference ought to develop along the lines drawn up at the Hamburg Meeting in 1932. Thus, according to Nordström, it ought to be more of a Hydromechanical Congress than a Tank Superintendent Conference, while others, among them myself, were in strong favour of keeping the Conference mainly for people who earned their living by tankery and who were responsible for giving shipbuilders and ship operators advice and information based on the results of experiments with ship models.

In 1954 at the Scandinavian Conference Dr. Nordström, who was at that time Chairman of the Standing Committee (later the Executive Committee) proposed the new name "The International Conference on Ship Hydrodynamics." The Conference rejected this and adopted instead the name "The International Towing Tank Conference, ITTC," which has been in use since then.

A new crisis arose towards the end of the 1960's. Again the cause was the difference in opinion between those who wanted a conference mainly for tankery and those who wanted a hydrodynamic conference in a broader sense. This time the crisis was more serious, and according to my judgement the Conference in 1969 in Rome (the twelfth) could have been the last one.

It was mainly the efforts of Dr. W.E. Cummins, of NSRDC, that helped solve the problem. Dr. Cummins was at that time, like me, a member of the Executive Committee. He put forward the idea of the Advisory Council. The Advisory Council was established by the Conference in 1972 in Berlin and Hamburg. Its functions were added to the Rules of Organization at the same Conference. In short it can be said that the Advisory Council gives the main and well-established towing tanks control over matters of organization and policy with reference to the Conference.

The usefulness and the benefit of the Conferences to the towing tank establishments could of course be discussed at length, particularly if weighed against the considerable costs involved. However, I hope to have the opportunity at a subsequent occasion to describe and discuss the work in the International Towing Tank Conference in greater detail.

LECTURE II

A EUROPEAN SHIP MODEL BASIN: THE SWEDISH MARITIME RESEARCH CENTRE (SSPA)

INTRODUCTION

In connection with the expansion in Swedish shipbuilding industry in the 1930's and as a result of the needs of the Swedish Navy it was considered necessary to build a ship towing tank of modern size and dimensions. This establishment, which is now called the Swedish Maritime Research Centre (SSPA), was located in Gothenburg and opened in 1940.[4]

After a modest start, based on the work in the ship-model towing tank, the activities of SSPA have passed through an intensive expansion, especially during the 1950's and 1960's when Sweden became second to Japan as a shipbuilding nation. The Swedish Maritime Research Centre was provided with large resources both in personnel and in experimental facilities.

This establishment at first was named the Swedish State Shipbuilding Experimental Tank (statens skeppsprovningsanstalt) (SSPA). On 1 July 1981, it was renamed The Swedish Maritime Research Centre (marintekniska institutet); for the sake of convenience the old abbreviation, SSPA, was kept after the renaming.

ORGANIZATION

The Swedish Maritime Research Centre, which is a state institution under the jurisdiction of the Ministry of Industry, has been in operation since 1940 in Gothenburg. The establishment is intended for use in both testing and research work. Under the supervision of the Director General, the organization consists of three technical departments and one administrative, viz:

1. <u>Maritime department</u>: propulsion, ship dynamics, hydrodynamic research, naval ships, offshore, marketing, library.
2. <u>Ship projects department</u>: hull form design, ship resistance, propulsion, fuel economy.

3. <u>Works department</u>: towing basin, cavitation tunnels, maritime dynamics laboratory, computer simulation, workshop.

4. <u>Administrative department</u>: economy, staff, service.

The SSPA has today about 170 employees, about 40 of which are university graduates, five with a doctor's degree.

There is a price list for model manufacturing, model tests, technical investigations and research work which covers the total cost for the work concerned. Customers include the Swedish Navy (Royal Swedish Naval Administration), the Swedish Board for Technical Development, the Delegation for Transport Research, Ship Yards, Ship Owners, and Offshore Industry, Grants and Foundations connected with SSPA, as well as our own research work (sponsored by the Swedish Government).

Only a minor part of the research results obtained are generally published. Most of the results from tests and research are given in confidential reports to the Navy, to civilian customers, or are recorded in unpublished internal reports. The research work sponsored by various grants and foundations and our own research are normally reported either in the series of "Publications of the Swedish Maritime Research Centre" (Meddelanden fran SSPA) or as a "General Report" (Allman rapport).

MAIN FACILITIES

Towing Tank (Figure 1)

Basin: Length = 260 m, Width = 10 m, Depth = 5 m

Towing carriage: Max. speed 14 m/s

Wavemaker: Dimensioning wave: Length 12 m
Height 0.4 m

Regular waves: Plunger type wavemaker

Maritime Dynamics Laboratory (Figures 2, 3)

Basin: Length = 88 m, Width = 39 m, Depth = 0 to 3.5 m

Multiple component carriage: Maximum speed in lengthwise direction 3.5 m/s, in transverse direction 3.0 m/s

Maximum angular velocity of turntable 30 deg/s

Wavemakers along two sides for regular and irregular waves

Dimensioning wave: Length = 9 m
Height = 0.4 m

Cavitation Tunnel No. 1: (Figures 4, 5)

Test section length = 2.6 m

Test section area = 0.7 m × 0.7 m or 0.5 m × 0.5 m

Cavitation Tunnel No. 2: High speed test section (Figure 6):

Test section length = 2.1 m

Test section diam. = 1.0 m

Maximum water speed = 23 m/s

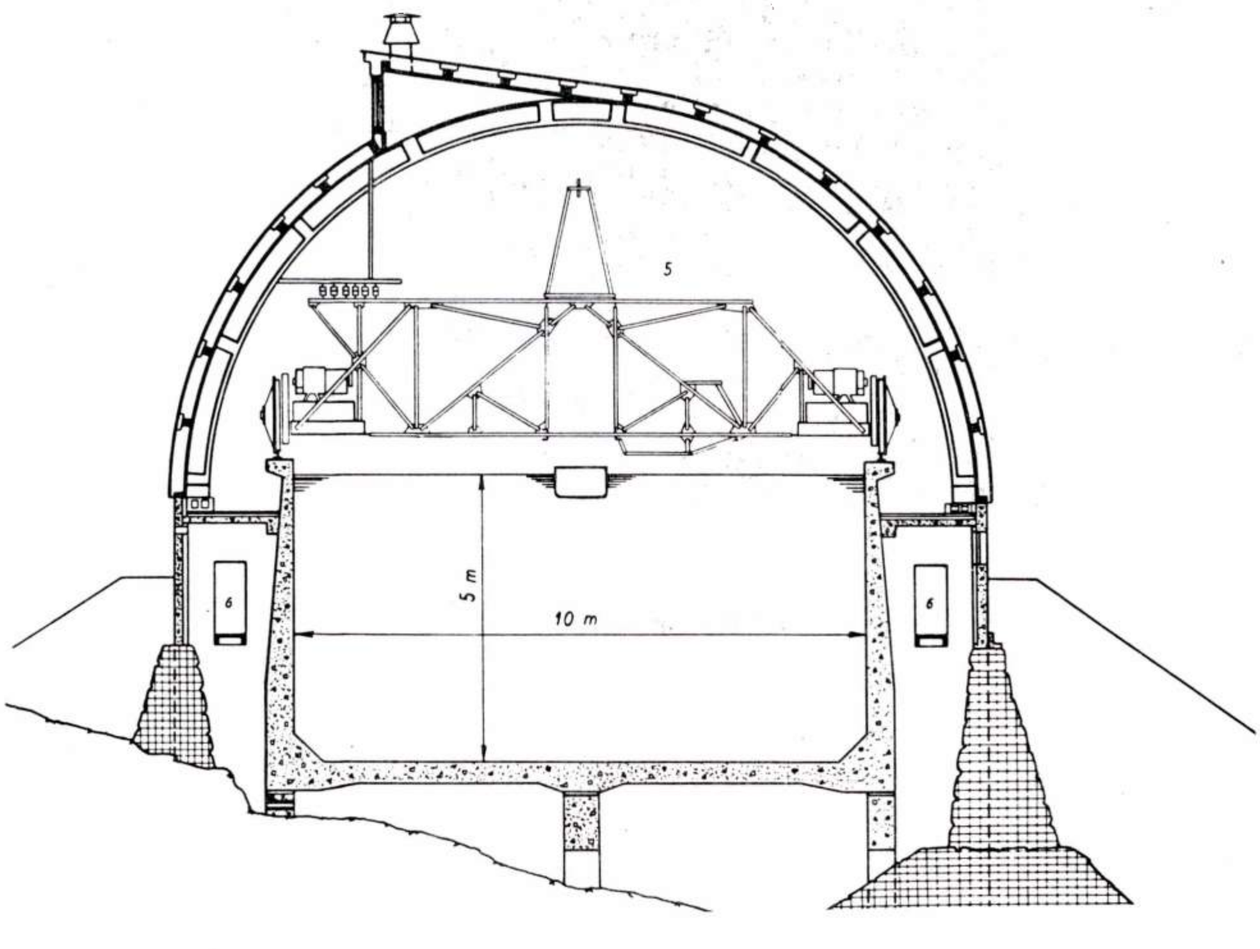


Figure 1 - Main Towing Tank at the Swedish Maritime Research Centre (From Edstrand[4])

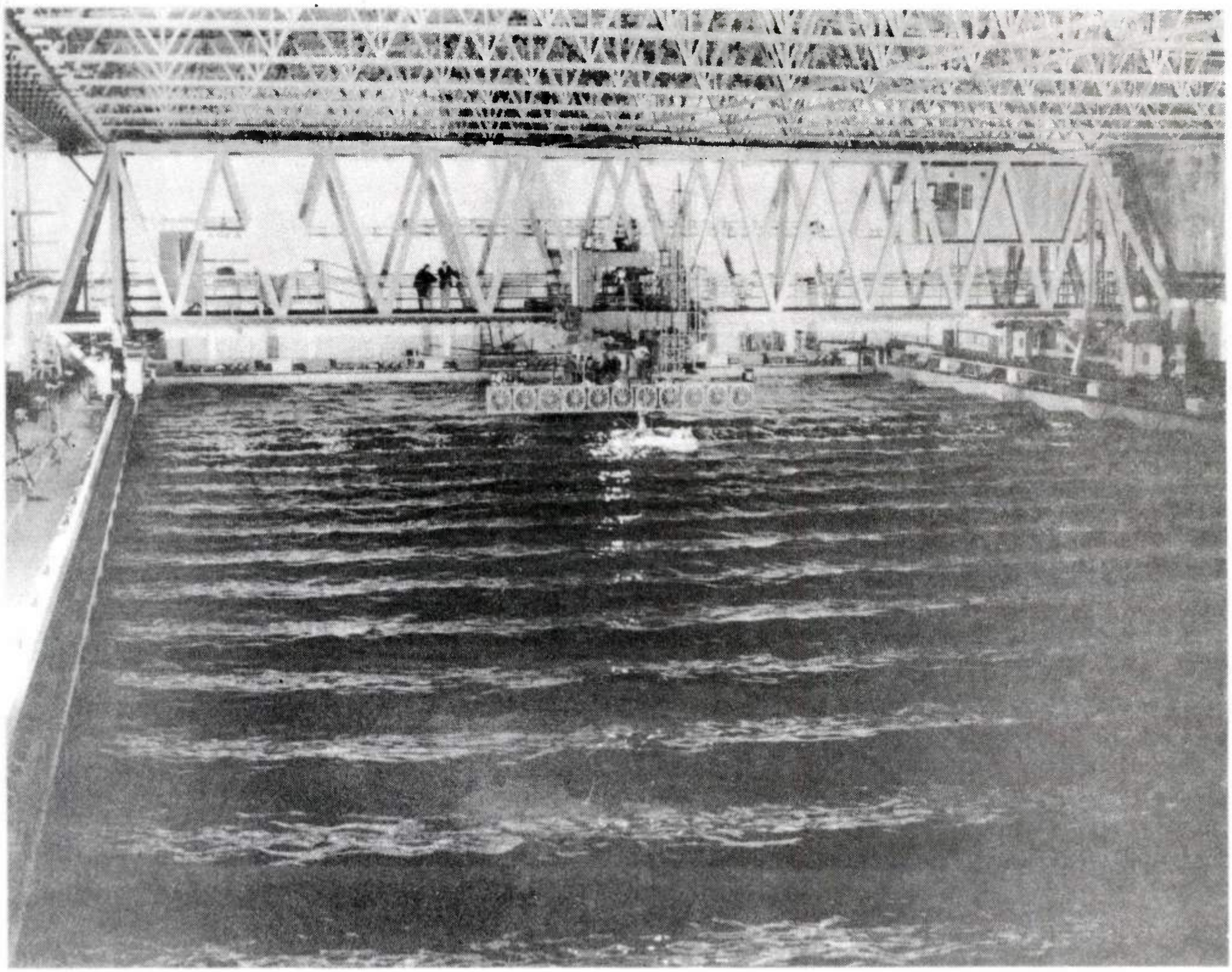


Figure 2 - Basin and Carriage at the Maritime Dynamics Laboratory

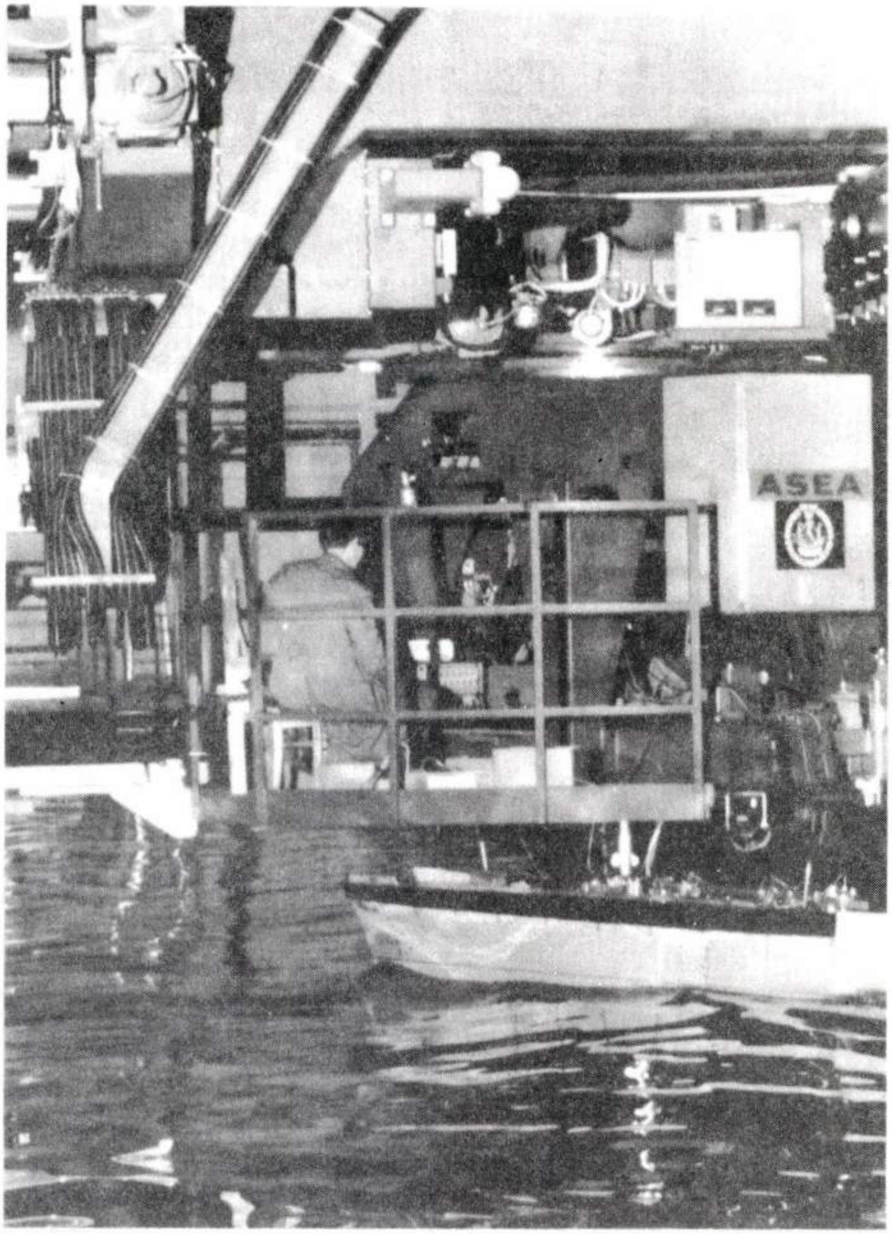


Figure 3 - A Fast Patrol Craft Maneuvered in Oblique Sea Condition in the Maritime Dynamics Laboratory

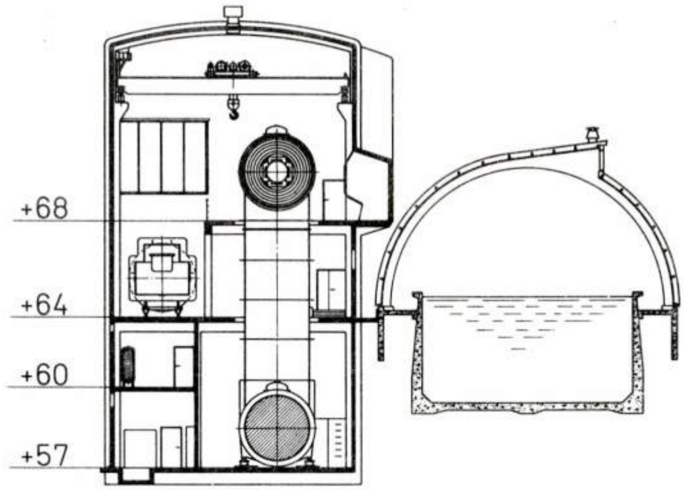


Figure 4a - Cross Section of the Laboratory and
the Adjacent Towing Tank

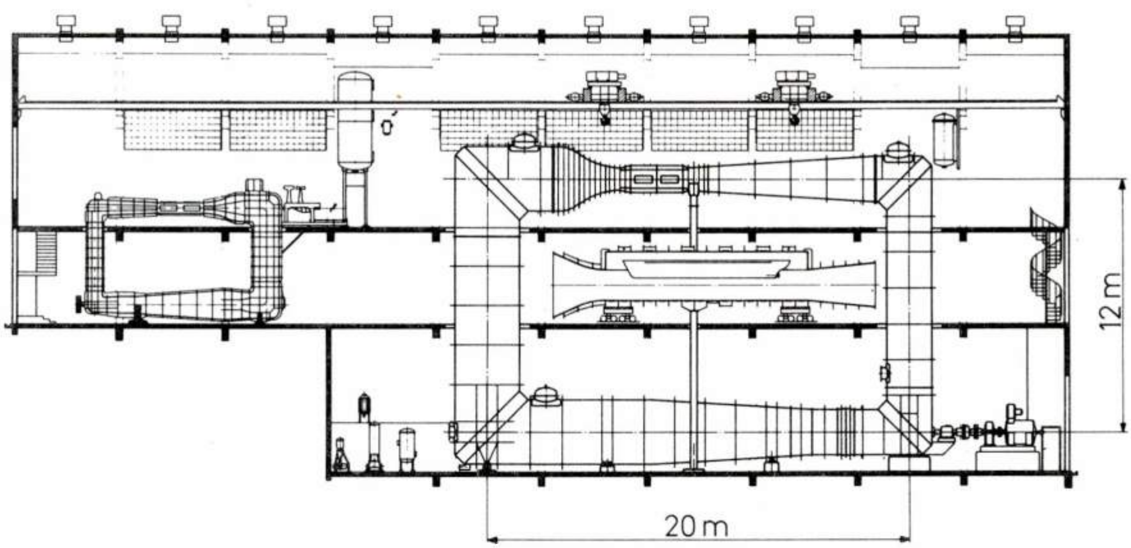


Figure 4b - Longitudinal Section with the Two Cavitation Tunnels. The Larger Tunnel is Shown with its Smaller Test Section in Place. The Large Test Section which is Intended for Ship Models, is Stored in the Place Reserved for it.

Figure 4 - The Cavitation Laboratory at the Swedish Maritime Research Centre (From Edstrand[5])

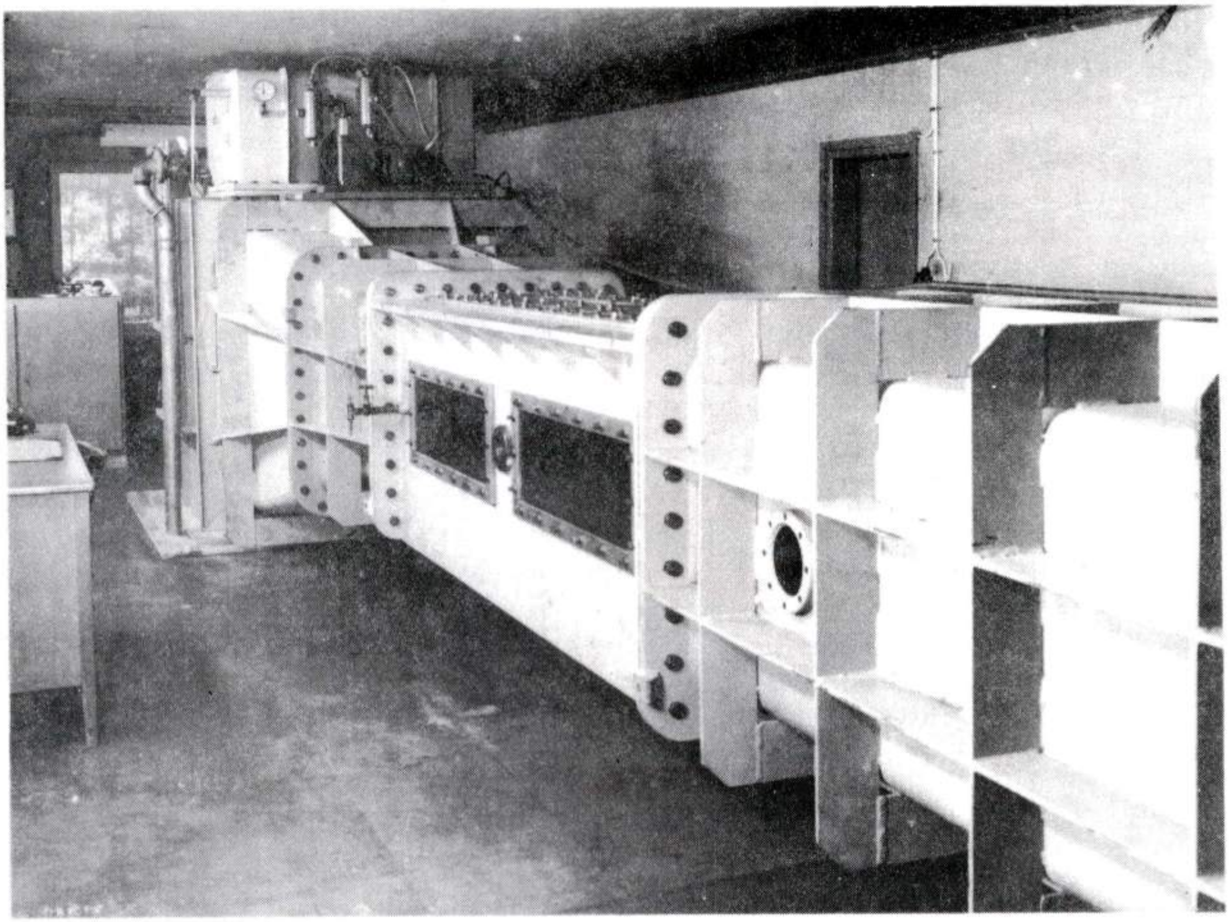


Figure 5 - Cavitation Tunnel Number 1
(From Edstrand[5])

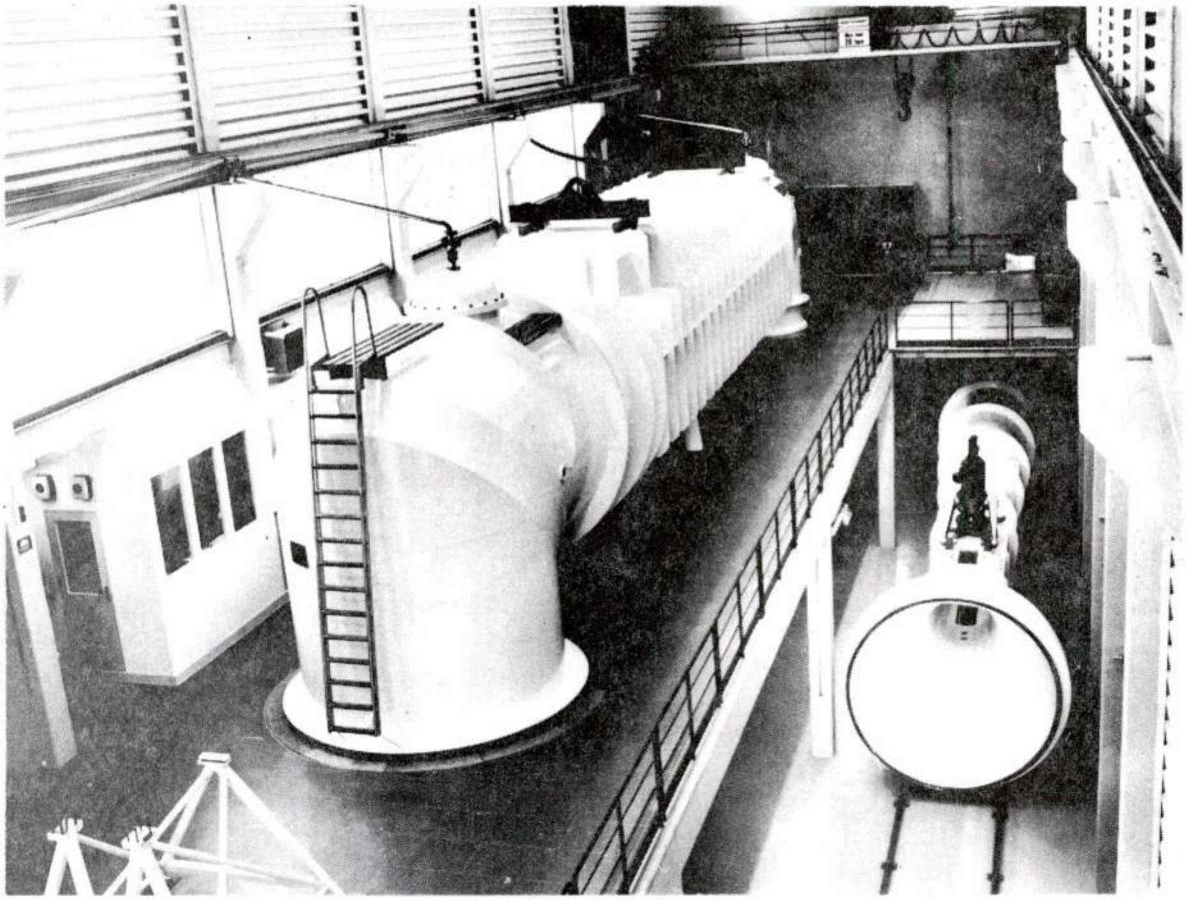


Figure 6 - Cavitation Tunnel Number 2
(From Edstrand[5])

Cavitation Tunnel No. 2: Low speed test section for ship models:

Test section length = 9.6 m

Test section area = 2.6 m × 1.5 m

Maneuvering Simulator: Hybrid computers, exchangeable control panels in bridge mock-up (Figure 7).

It ought to be mentioned here that with the arrival of computers new theoretical calculation methods and mathematical models were developed which have proved to be valuable complements and in some cases alternatives to the more expensive laboratory experiments.

PROGRAM

The Swedish Maritime Research Centre has established the following program.

Ship form optimizing:	Model tests, preliminary design, power estimations, full scale predictions.
Propeller design:	Calculations and model tests for all kinds of propellers and thrusters.
Cavitation:	Theoretical and experimental investigations, including effects on propeller efficiency, erosion vibration and noise.
Maneuvering:	Theoretical and experimental studies, analyses of model tests and ship trials, simulator training of ship officers and pilots.
Seakeeping:	Model tests in regular and irregular waves, calculation of motions and forces on bodies in water, analyses of model tests and ship trials.
Offshore:	Model tests of all kinds of offshore constructions, predictions of sea loads and motions.
Research and consulting:	Fundamental and applied research and consulting within the different branches of hydromechanics.

FURTHER DISCUSSION OF FACILITIES AND WORK[6]

As mentioned above, especially during the 1950's and 1960's, SSPA was provided with new facilities. Among the large investments from this period are:

Figure 7 - Maneuvering Simulator, where Ship Officers and Pilots are Trained. One Week Courses in the Ship Handling Simulator Include Maneuvering in Deep and Shallow Water, Man-over-board and Other Emergency Maneuvers, Mooring and Anchoring, Maneuvering in Narrow Fairways and Port Approaches, etc. All Kinds of Ships and Different Load Conditions Can Be Simulated Together With Any Fairway or Port.

1. Wavemaker for studies of seakeeping characteristics
2. Cavitation tunnel 1
3. Computer facility with ship maneuvering simulator
4. Cavitation tunnel 2

The development towards larger and faster ships during the 1950's and 1960's directed the interest towards cavitation, vibration, and noise problems. Much still remains to be done in this sector, and it is of great importance both for energy economy and the comfort on board ships.

With the large No. 2 cavitation tunnel, SSPA introduced a new idea by which a standard size hull model can be fitted into the test section. This makes possible better modeling of stern flow conditions. During the past 12 years this tunnel has proved to be a valuable tool for predicting and avoiding the risk of stern vibrations due to propeller force fluctuations or flow separation. The long list of customers includes shipyards from all major shipbbuilding countries in the world. The cavitation tunnels of SSPA are further discussed in Chapter 5.

Maritime Dynamics Laboratory

At the beginning of the 1970's while Sweden was still one of the leading shipbuilding nations, the Swedish Government decided on a large investment at the Swedish Maritime Research Centre. After pressure from the shipbuilding industry, shipping companies, the Swedish Navy, and the National Swedish Board of Shipping, it was decided that a new large laboratory should be built--the Maritime Dynamics Laboratory (MDL). This facility is now in full operation and is one of the trumps of the Swedish Maritime Research Centre in the keen international competition.

The new Maritime Dynamics Laboratory has a wide rectangular basin with a "multimotion" carriage and wave generators along two adjacent sides. Thus, it is well equipped for the role of a seakeeping and maneuvering laboratory. However, additional features are incorporated to meet the special demands for testing other marine structures designed for the off-shore industry.

The basin, built on solid rock, is 88 m long and 39 m wide. The water level may be varied from dry bottom to a height of 3.5 m in about 60 hr, normal "deep water" being 3.0 m. A special 1000-m^3 storage basin provides facilities for rapid minor adjustments of the water level. All experimental equipment is designed for correct positioning in relation to the water surface. The main carriage has a track span of 35 m and the total weight with subcarriages for transverse and turning motions is some 165 tons. The computer-based carriage control system includes programs for towing or tracking a model in any motion across the basin, traveling at linear speeds up to 3.5 m/s and turning at a rate of 30 deg/s. An auto-pilot maybe used to make a free-sailing model follow the carriage closely along a prescribed course. Alternately, the carriage may be required to "hunt" the model, when the model is disturbed by waves or turning in response to helm orders.

The present demands for tests of offshore structures in waves, tide, and wind have required additional equipment. Thus, for example, the effects of homogeneous current past a moored platform are simulated by towing the bottom anchors on a special trailer rolling on the bottom of the basin. The modeling of the mooring cables presents a difficult problem of its own. A battery of fan blowers fastened to the carriage is used to generate wind in any direction.

Computer Center and Ship Maneuvering Simulator

The variety of results obtained in the various hydrodynamic laboratories are translated into predictions of full-scale behavior of ships or structures in a computer-aided process that makes extensive use of theory and previous experience. A special facility is the hybrid computer with the Maneuvering Simulator, dedicated to ship handling research and training.

Although computer-aided simulation of vehicle dynamics had previously been applied to aircraft pilot training and submarine design, the SSPA real-time ship maneuvering simulator of 1967 was the first such facility dedicated to surface ship problems. It incorporated a simple electronically generated out-of-window scenery. The present "bridge-mock-up" was built in 1973, as one of the last achievements of the carpenters of the Eriksberg Shipyard in Gothenburg. This shipyard is now closed.

The computer capacity has been continuously expanded; it now includes two multi-use hybrid systems. The versatility of this ship handling simulator is based on extensive software for ship dynamics and control in open or restricted waters.

Activities for Merchant Ships

Merchant ship technology still dominates the activities of the Swedish Maritime Research Centre. At present, more than 40% of the capacity is used for work Swedish and foreign shipyards and shipping companies. The foreign share is increasing and is today about half the total. The work in marine technology is characterized by the demand for more extensive investigations of current ship types than was needed for the comparatively simple ships that earlier dominated shipbuilding production. Moreover, the growing competition among shipyards increases the demands for optimal designs. Among essential factors influencing shipbuilding development, the following can be mentioned:

1. Fuel prices, drastically increased during the latter part of the 1970's, lead to increasing demands for ships with low energy consumption. Investigations aiming at decreasing the fuel consumption for existing vessels as well as for new projects dominate the activities at present.

2. Increased demands from authorities and organizations concerning seaworthiness, vibrations and noise result in great demands for further developments.

3. In connection with changed routines of loading, new types of ships have been developed, such as container, roll on/roll off (RO/RO), and supply ships and various kinds of product carriers.

During the 1950's and the 1960's practically all of SSPA's commissions came from the shipyards; now, however, the technical experts of the shipowners themselves are more likely to take the initiative or to actively take part in the development work. Extensive projects are nowadays carried out for individual shipping companies or groups of shipping companies before these groups make inquiries to the shipyards.

The choice of a ship's dimensions, the lines plan, propeller arrangement, and propeller design have a great effect on the energy consumption. A good way of reducing fuel consumption is to thoroughly study these factors at the projecting stage.

For existing ships it could be valuable to investigate the optimal operating conditions with regard to trim, draught, and choice of power utilization.

The importance of maneuvering quality and seakeeping performance have increased in connection with unconventional types of ships having new hull design and often extreme load distributions.

Navy Activities

About 15% of the capacity of SSPA is used for work in the Navy sector. The collaboration with the Swedish Naval Forces has been of great importance for the technical development of SSPA. Many of the technical problems of merchant ships have appeared much earlier and in more evident ways on military ships. For example, the demand for low noise levels on submarines has increased our knowledge of hydro-acoustic and flow noise problems. The demand for highly maneuverable minesweepers resulted in studies of special steering arrangements. Response to the need for motor torpedo boats with high speed propellers has developed knowledge of cavitation erosion and vibration.

Offshore Technique

The interest in exploring and exploiting oil and gas resources at sea has caused intensive technical development. Semisubmersibles, jackets, jack-up rigs, floating factories, oil storage systems, mooring systems, support systems, and supply vessels are examples of technically advanced novelties. They all demand competent planning and considerable development and testing.

In the beginning of the 1970's SSPA started work in the offshore sector. When the new Maritime Dynamics Laboratory was completed at the end of the decade, it of course became an important resource for experimental investigations in this field.

The program includes the development of components as well as more complete investigations of whole systems. Forces and movements of structures and constructions meeting wind, waves, and current can be studied and determined under realistic conditions.

All indications are that the engagement of SSPA in the offshore sector will considerably increase in the future. Many Swedish industrial and shipping companies are involved in this sector and they often ask SSPA for service and assistance when planning and designing new products. For example, Gotaverken Arendal has developed a new four-column semisubmersible which has drawn great attention and which already has been sold to several customers. Swedyards Development Co. is working with floating processing plants tested at SSPA. The shipowner company Stena Line has built well known supply vessels at the shipyeard Oresundsvarvet.

The Swedish Maritime Research Centre's intensive activities in offshore development have aroused great interest in the international market and have resulted in commissions of many kinds. One recent and remarkable study concerns the installation of a production platform in the North Sea. The jacket was designed by John Brown Offshore Ltd. in London and is owned by Mobil. The installation will take place in 1983. The whole installation process has been studied in detail and optimized by model tests under simulated weather conditions in the Maritime Dynamics Laboratory. Some time ago an investigation of forces on large, full scale cylinders was carried out. This extensive investigation was ordered by Shell Developing Co. in Houston, U.S. It was financed by an international consortium.

Knowledge of forces on different types of steel constructions such as pontoons, risers and OTEC constructions exposed to current and wave forces is of great importance for strength and security reasons.

DEVELOPMENT TRENDS

The environmental problems around the Swedish coasts have been accentuated during the last few years by shipwrecks and oil dumping. The Swedish Maritime Research Centre has been engaged in reducing the risks and preventing catastrophes by helping to plan ports and fairways and their equipment and by training pilots and ships' officers in the Ship Handling Simulator. The resources for work of this kind were, of course, much increased when the new Maritime Dynamics Laboratory came into operation.

The arctic areas are at present of great interest. There are large resources of oil, gas, and minerals. Arctic offshore technology is developing rapidly and obviously Swedish industry can contribute to these activities. In this connection, it is very important to build up competence through intensified education, research, and experimental activities. Here SSPA represents an important resource.

Traditionally the Swedish Maritime Research Centre has specialized in hydromechanics. During the last few years the demands for complete solutions of technical problems have increased. Therefore, SSPA has found it necessary to broaden its range of activities. This is so especially when new staff members are recruited. Thus, there are today at SSPA experts in such areas as automatic control, structural mechanics, data processing and measuring techniques. This broadening in technical competence has proved essential in enabling the Swedish Maritime Research Centre to undertake the complicated commissions of today.

Much of the above material (Chapter 3) is taken from: Swedish Club News No. 1, 1982, "The Swedish Maritime Research Centre SSPA" by Dr. Hans Lindgren.[6]

LECTURE III

DEVELOPMENTS IN MERCHANT SHIP DESIGN AT THE SWEDISH MARITIME RESEARCH CENTRE (SSPA)

The development of very large tankers and bulkships and high installed engine shaft horsepower for containers and RO/RO ships was brought to a halt some years ago by the oil crisis. Tankers up to and above half a million tons deadweight (tdw) were then already ordered, container vessels of more than 1000,000 SHP were already delivered. Ten years ago car-ships could carry at most 500 cars. Today there are car-ships in operation that can carry more than 6000 cars. Compared with other means of transportation, the sea transport has, of course, a great economic advantage. For instance, the cost of energy to transport 1 ton of goods by flight, in kwh/ton km is about one thousand times more expensive than transport of 1 ton of oil by supertanker.

The economic importance of the relationship between cost of fuel and ship hydrodynamics has increased significantly during recent years. Ship hydrodynamics has always been an important research field. This research has now become an economic necessity. Some of the criteria for economical ship propulsion are directly coupled to factors such as hull, machinery, and fuel costs. Examples of other criteria are the quality of propulsion and the presence or absence of propeller cavitation, noise, and vibration.

An analysis based on the separation of the required propulsive power into the various resistance components and propulsive coefficients points to factors that influence overall efficiency. Large and full ships, such as tankers and bulk carriers, may increase efficiency through modest changes in dimensions. More slender, medium sized ships such as container and RO/RO ships, can often require more drastic design changes for optimum fuel efficiency.

Figure 8 shows the various components of propulsion and their relation to various items for an 80,000 ton dead weight (tdw) tanker.

THE 500,000 tdw TANKER

As mentioned above, the increase in size of tankers came to a halt in connection with the last oil crisis. The Uddevalla Shipyard in Sweden delivered a 499,000 tdw tanker, "Nanny" in November 1978. It is interesting to compare the main dimensions

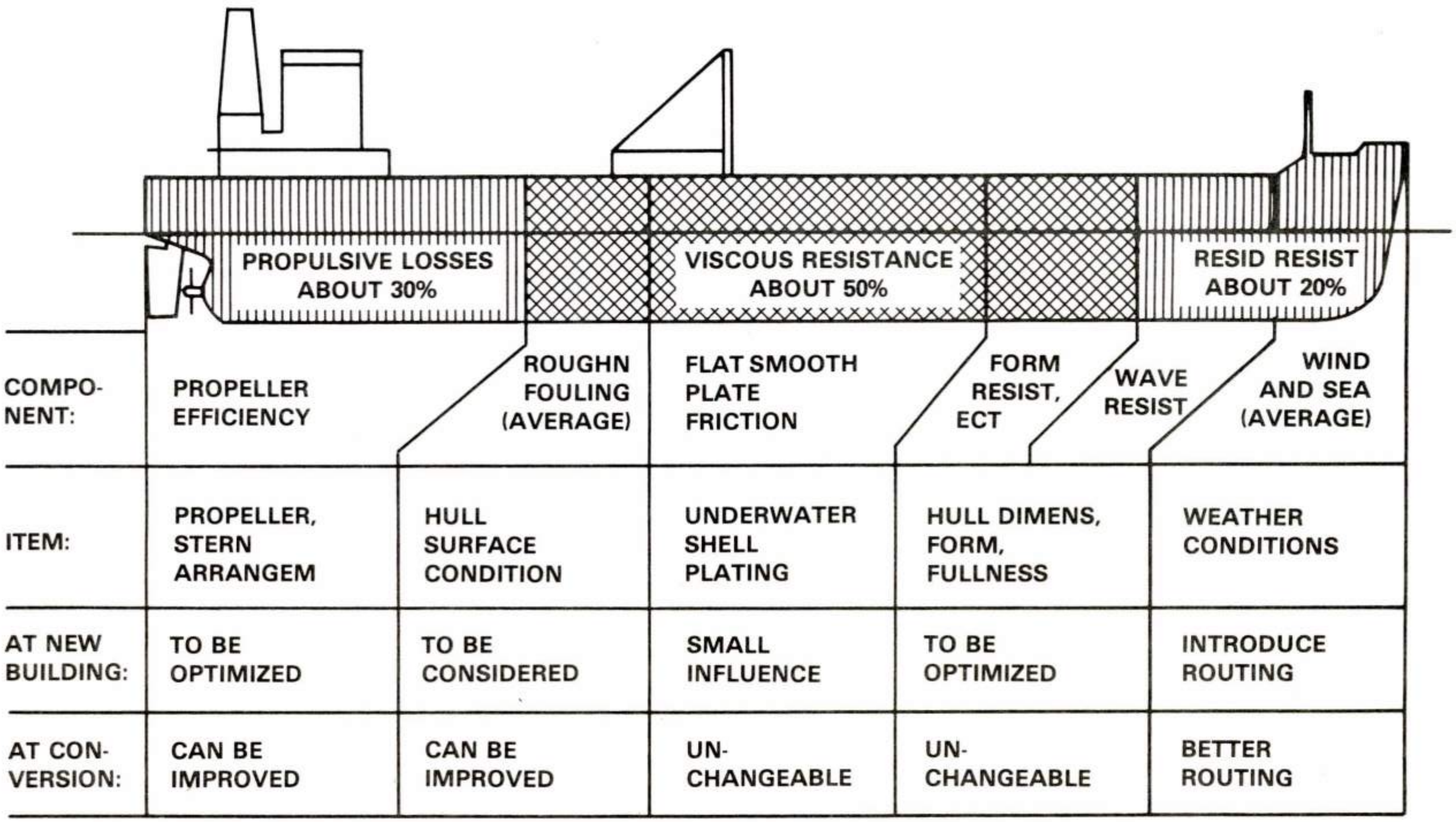


Figure 8 - Components of Propulsion for about 80,000 tdw Tanker and Relation to Various Items, Showing how Energy Can be Conserved at New Building and Conversion

of this ship with another tanker, "Josefina Thorden" delivered in February 1955 from the same shipyard and supposedly the biggest ship in Europe at that time.

	"Nanny"	"Josefina Thorden"
Tons Dead Weight	499,000	32,000
Shaft Horse Power	52,000	19,000
Number of Propellers	2	1
Length to Beam Ratio (L_{pp}/B)	4.4	7.5
Bow Shape	Cylindrical	Embryo Cylindrical
Afterbody Shape	2-skeg	U Form
Trial Trip	Nov 1978	Feb 1955

The 499,000 tdw tanker "Nanny" has two stern skegs, or rather, gondola skegs. This arrangement was extensively tested in the large cavitation tunnel. The areas between the skegs (or gondolas) turned out to be especially sensitive to cavitation.

The most remarkable figure in the table above is, of course, the value of $L_{pp}/B = 4.4$. "Nanny" is the widest ship ever built. The beam is 79 m (259 ft). The ship has excellent performance with a very low noise level and remarkably good fuel economy.

MERCHANT SHIP ECONOMY

Among the various expenses in shipping, fuel costs have come into focus. During the last 7 years the price of marine diesel oil as well as of heavy fuel oil has been multiplied by about eight. Other costs, new building costs for example, have doubled during the same period.

Figure 9 shows the reduction of required freight rate (RFR) due to 10% improvement of building, fuel, and crew costs.[7] To reduce building and crew costs significantly, questions of subsidies and flag must be raised. The fuel costs, however, which mainly depend on the hydrodynamical quality of the ship, can be decreased through experimental work of a ship model laboratory.

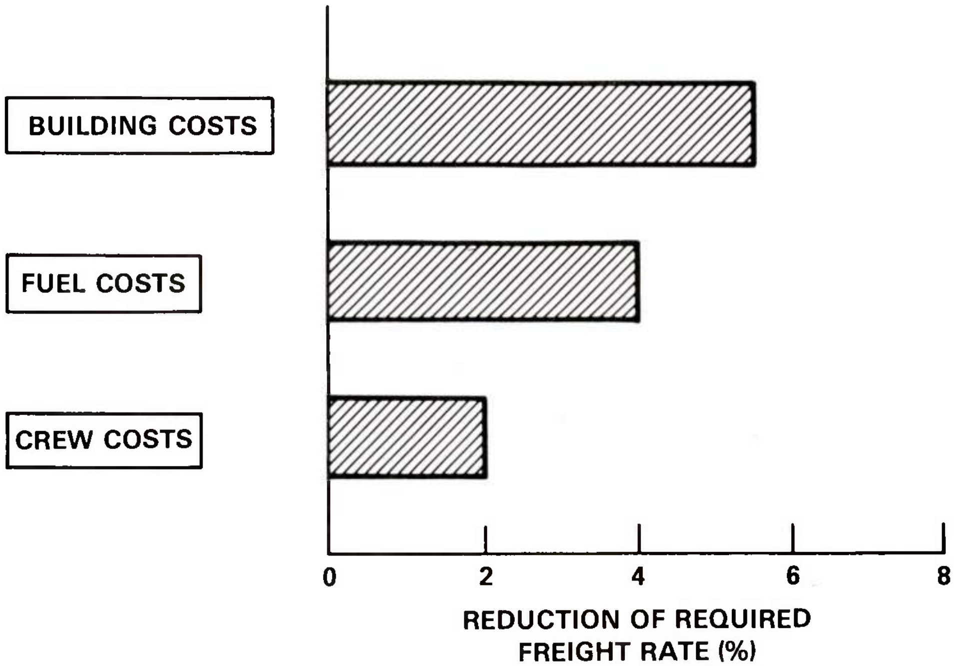


Figure 9 - Reduction of Required Freight Rate Due to a 10 Percent Improvement of Building Costs, Fuel Costs, and Crew Costs (From Williams[7])

FUEL ECONOMY FOR MERCHANT SHIPS

A thorough investigation has been carried out by Åke Williams at SSPA of the fuel economy of two common types of merchant ships. Mr. Williams is head of the Ship Projects Department at SSPA. The results of the investigation are published in SSPA publication No. 87, 1980.[8] Some of the main results of this investigation will be given here.

Williams used the diagram in Figure 10 in selecting two representative ships for the analysis. This diagram illustrates the tendency of relative fuel costs to change with hull steelwork price for a number of ship types. The following two ships with different cost pictures were selected for these analyses of propulsive economics:

A) 12,000-m^3 displacement RO/RO vessel. Deadweight about 6000 tons. Speed: 18 knots.

B) 1000,000-m^3 displacement tanker. Deadweight about 85,000 tons. Speed: 16 knots.

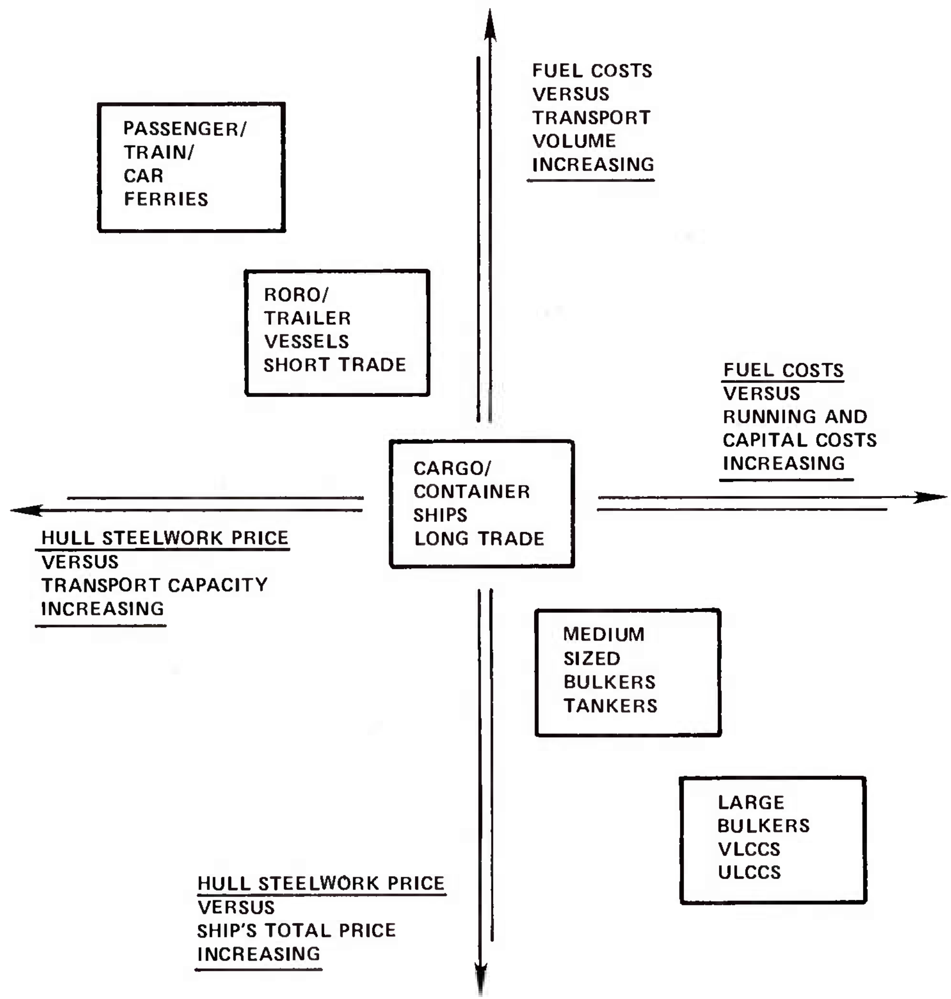


Figure 10 - The Tendency of Relative Fuel Cost and Hull Steelwork Price for a Number of Ship Types
(From Williams[8])

Ship A (the RO/RO vessel) has rather high fuel costs in relation to achieved transport volume and a fairly expensive hull steelwork in relation to transport capacity. These costs are relatively low for Ship B (the medium-sized tanker). However, the fuel costs for the tanker are high in relation to other running and capital costs. Also, hull steelwork price versus total price is considerably higher for a tanker than for a RO/RO vessel. The following data and cost figures are assumed for the two ships:

	RO/RO	Tanker
Length between Perpendiculars, m	140	240
Displacement, m^3	12,000	100,000
Block Coefficient (C_b)	0.66	0.80
Speed, knots	18	16
Propulsive Power, MW	6.0	12.6
Propeller, RPM	150	110
Total Price of Ship (U.S.$)	20 million	40 million
Hull Cost of total	30%	40%
Outfit Cost of total	40%	30%
Machinery Cost of total	30%	30%
Annual Cost of Cap. Recov.	20%	20%
Heavy Fuel Oil, U.S.$/ton	160	160
Days at Sea per Year	250	300

Tests with variations of speed, length, and fullness for the two ships were carried out. The influence of speed (Figures 11a and 12a) shows us that the rise of fuel costs within the speed interval is considerable for both ships. From that point of view, slow steaming means substantial cost reduction; the disadvantage is the preserved high machinery capital cost.

From the length variation (lower diagrams Figures 11 and 12) it is evident that longer ships of less fullness will be more economical when the fuel price rises above the other costs.

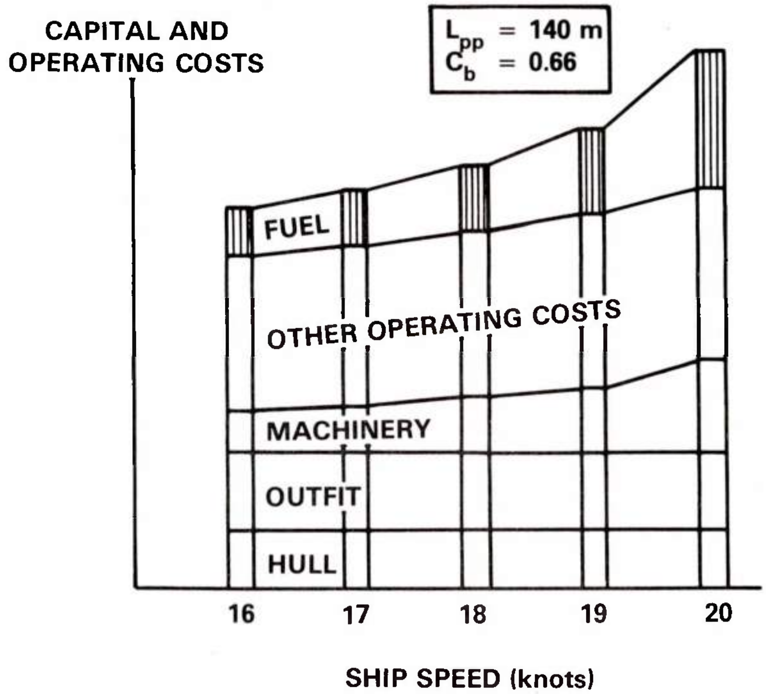


Figure 11a - Speed Variation

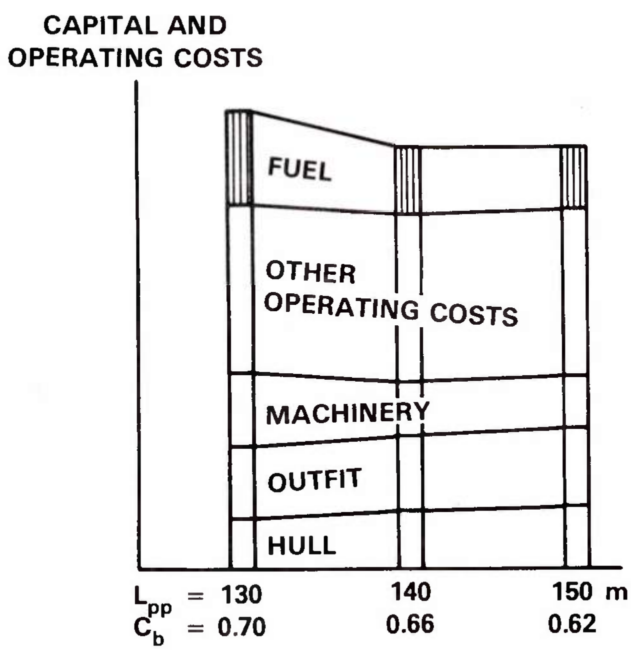
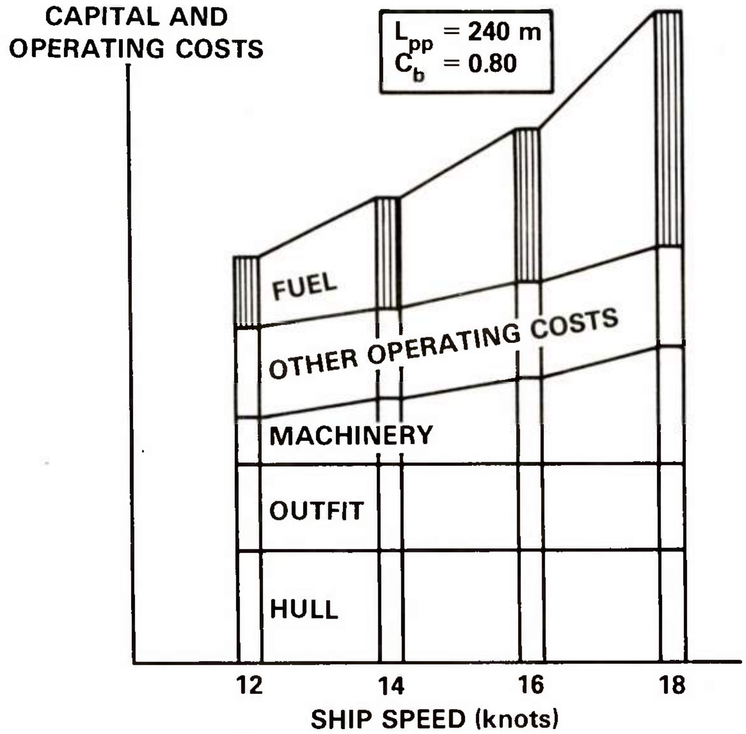


Figure 11b - Length and Fullness Variation at a Velocity of 18 Knots

Figure 11 - Relative Capital and Operating Costs for 12,000-m^3 Displacement RO/RO (From Williams[8])



Fgiure 12a - Speed Variation

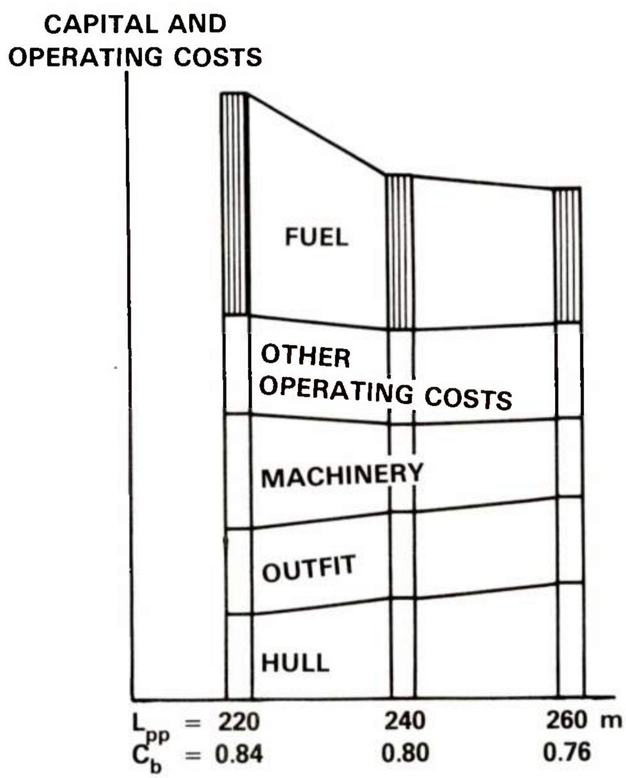


Figure 12b - Length and Fullness Variation at a Speed of 16 Knots

Figure 12 - Relative Capital and Operating Costs for 100,000-m^3 Displacement Tanker

(From Williams[8])

The influence of hull length and fullness can be further studied in Figures 13 and 14. Required power for the extremely full and short tanker is nearly three times as high as for the tanker with the finest and longest hull. Most of today's tankers seem to be nearer the first mentioned ship. The average ship of this class tested by SSPA after 1974 has a mean block coefficient of 0.82 and length approximately 230 m.

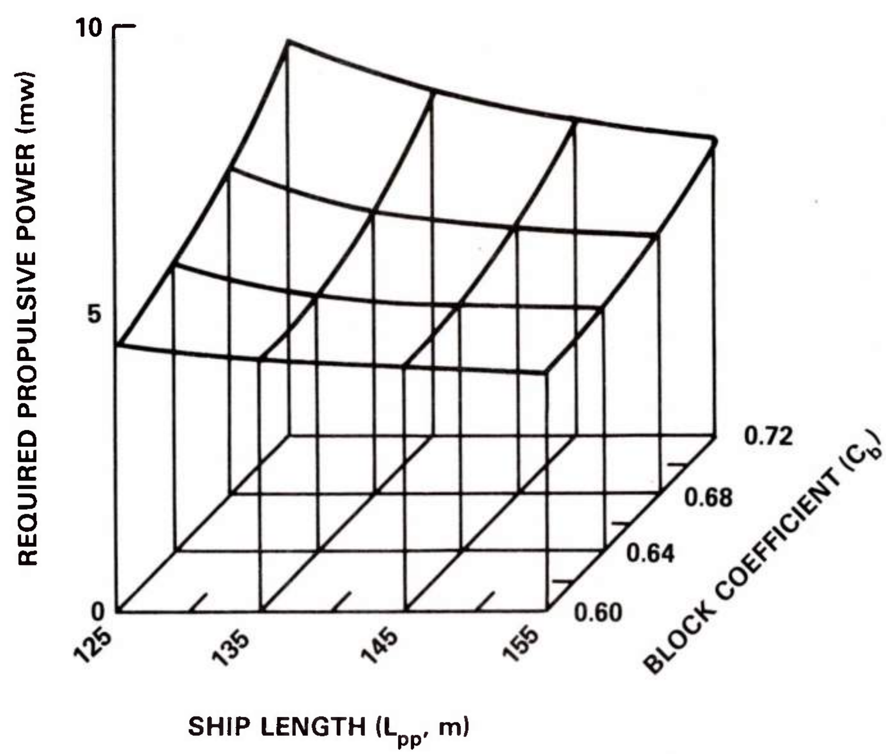


Figure 13 - 12,000-m^3 Displacement RO/RO. Required Propulsive Power Versus Hull Length and Fullness. Speed is 18 Knots.
(From Williams[8])

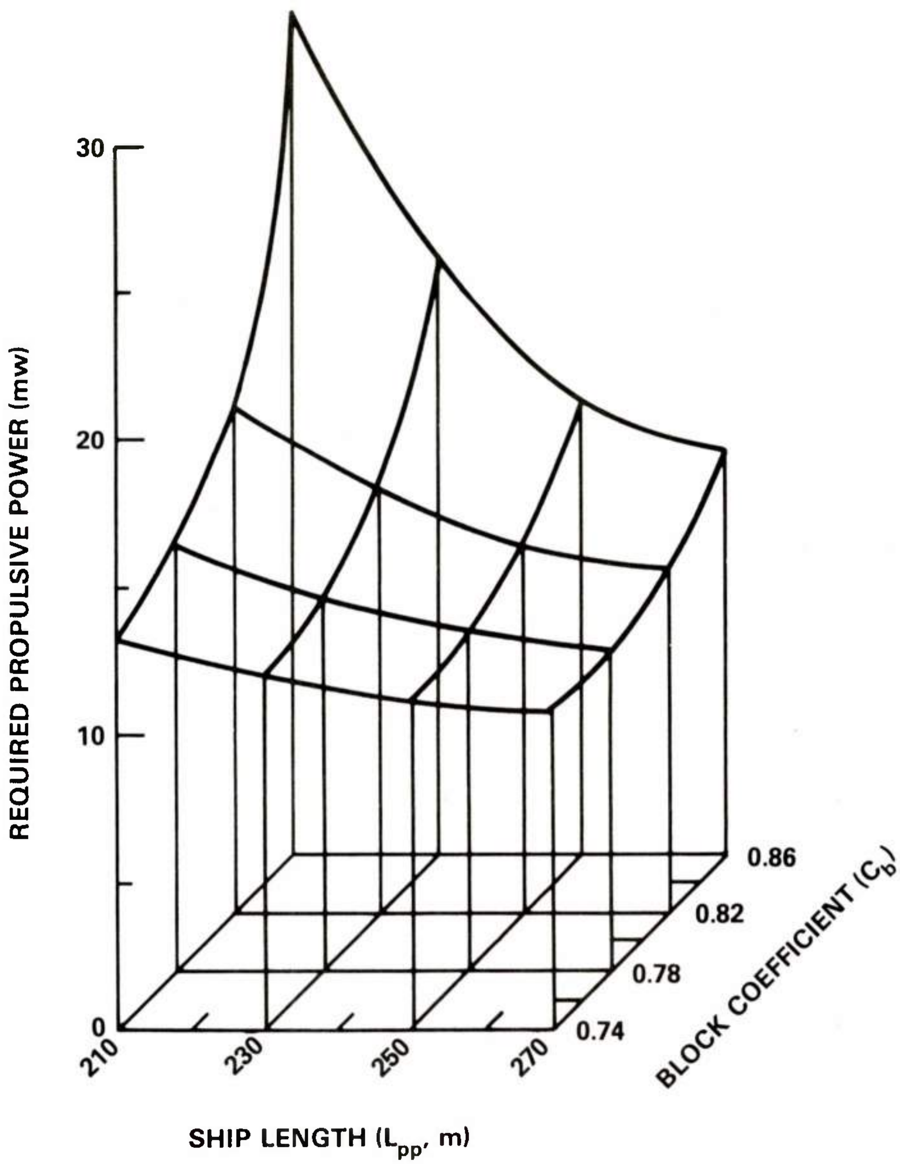


Figure 14 - 100,000-m^3 Displacement Tanker. Required Propulsive Power Versus Hull Length and Fullness. Speed is 16 Knots.
(From Williams[8])

Reduction of required propulsive power is also possible by changing other hull dimensions (if allowed), displacement (if lighter hull), propeller RPM and propeller blade rate. These parameters have been varied systematically, keeping the block coefficient constant (Figure 15) and alternatively with the block coefficient variable (Figure 16). For both vessels the attainable savings in shaft horsepower are considerable, much more than is commonly known. It should also be noted that a reduction of propeller RPM may be as efficient as an increased hull length. A propeller RPM reduction by 25% is quite realistic, whereas the designer can have difficulties getting approval of the extension of the hull length by a few percent.

THE COMPONENTS OF SHIP RESISTANCE AND PROPULSION

In Figure 17 the components of calm water resistance have been separated. On two occasions, 1957 and 1978, the International Towing Tank Conference (ITTC) has recommended methods for prediction of ship resistance and propulsive power from model tests. In the 1978 method, the main components of total resistance are defined as viscous resistance, wave making resistance, and spray resistance, with subcomponents as indicated in Figure 17. The earlier prediction procedures were based on a simpler division of the ship resistance into frictional and residual resistance.

Both methods generally designated ITTC-57 and ITTC-78, are illustrated in Figure 18, where the resistance components for the RO/RO vessel and the tanker are calculated (partly from model tests). Flat plate friction and hull form influence on viscous resistance is substantially higher for the tanker. The hull form influence is from the hull fullness. This component is thus not so easily influenced by hull shape at constant block coefficient. What is more affected by the hull form is the wave breaking and wave pattern resistance, mostly from the forebody, and viscous pressure and separation resistance, mostly from the afterbody. These components are more dominant for the RO/RO vessel.

Components making up the total propulsive power are listed in Figure 19. Propulsive components have been calculated for the RO/RO vessel and the tanker. The results are given in Figure 20.

CHANGES	HULL MAIN DIMENSIONS "CONSTANT BLOCK COEFFICIENT"				
	LENGTH	BREADTH	DRAFT	DISPL	BLOCK COEFF
PARENT	L	B	T	Δ	C_b
LENGTH CHANGE	XL	$X^{-1/2}B$	$X^{-1/2}T$	Δ	C_b
BREADTH CHANGE	$X^{-1/2}L$	XB	$X^{-1/2}T$	Δ	C_b
DRAFT CHANGE	$X^{-1/2}L$	$X^{-1/2}B$	XT	Δ	C_b
DISPL CHANGE	$X^{-1/2}L$	$X^{1/3}B$	$X^{1/3}T$	$X\Delta$	C_b

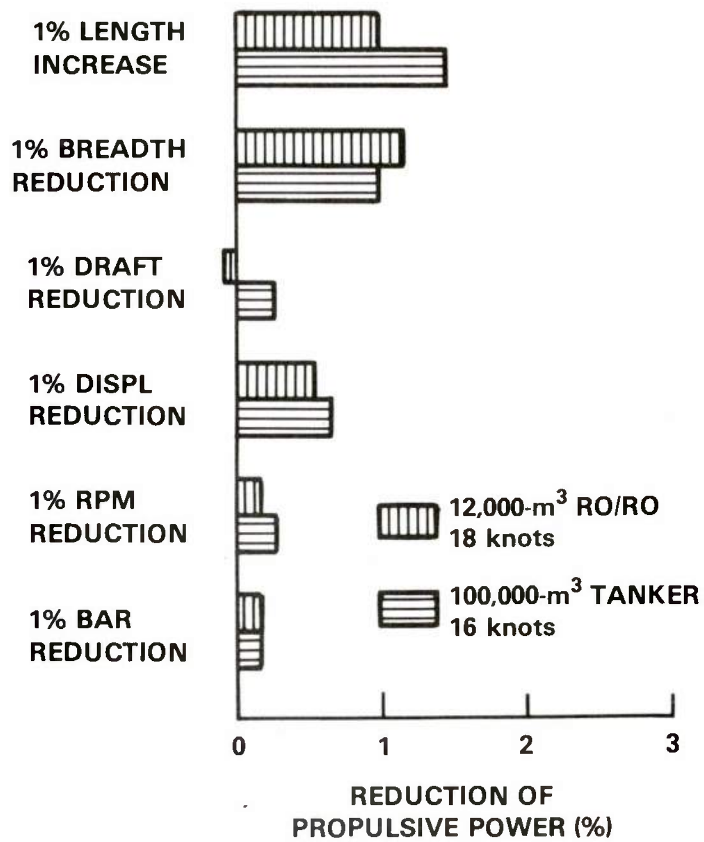


Figure 15 - Reduction of Propulsive Power due to Change of Main Hull Dimensions, Displacement, Propeller Rate of Revolution, and Propeller Blade Area. Constant Block Coefficient.

(From Williams[8])

CHANGES	HULL MAIN DIMENSIONS "VARIABLE BLOCK COEFFICIENT"				
	LENGTH	BREADTH	DRAFT	DISPL	BLOCK COEFF
PARENT	L	B	T	∇	C_b
LENGTH CHANGE	XL	B	T	∇	$X^{-1} C_b$
BREADTH CHANGE	L	XB	T	∇	$X^{-1} C_b$
DRAFT CHANGE	L	B	XT	∇	$X^{-1} C_b$
DISPL CHANGE	L	B	T	$X\nabla$	XC_b

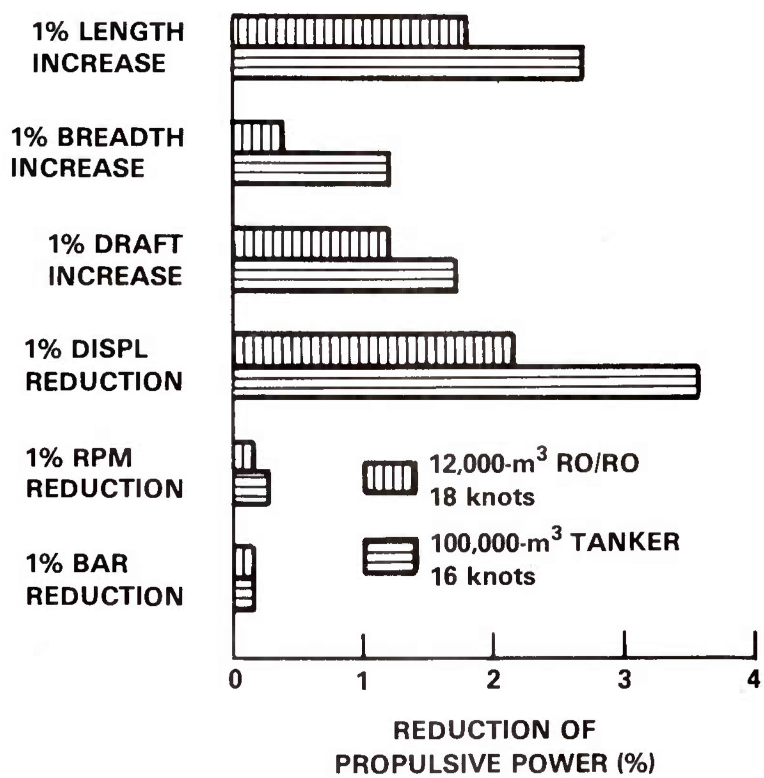


Figure 16 - Reduction of Propulsive Power due to Change of Main Hull Dimensions, Displacement, Propeller Rate of Revolution, and Propeller Blade Area. Variable Block Coefficient.

(From Williams[8])

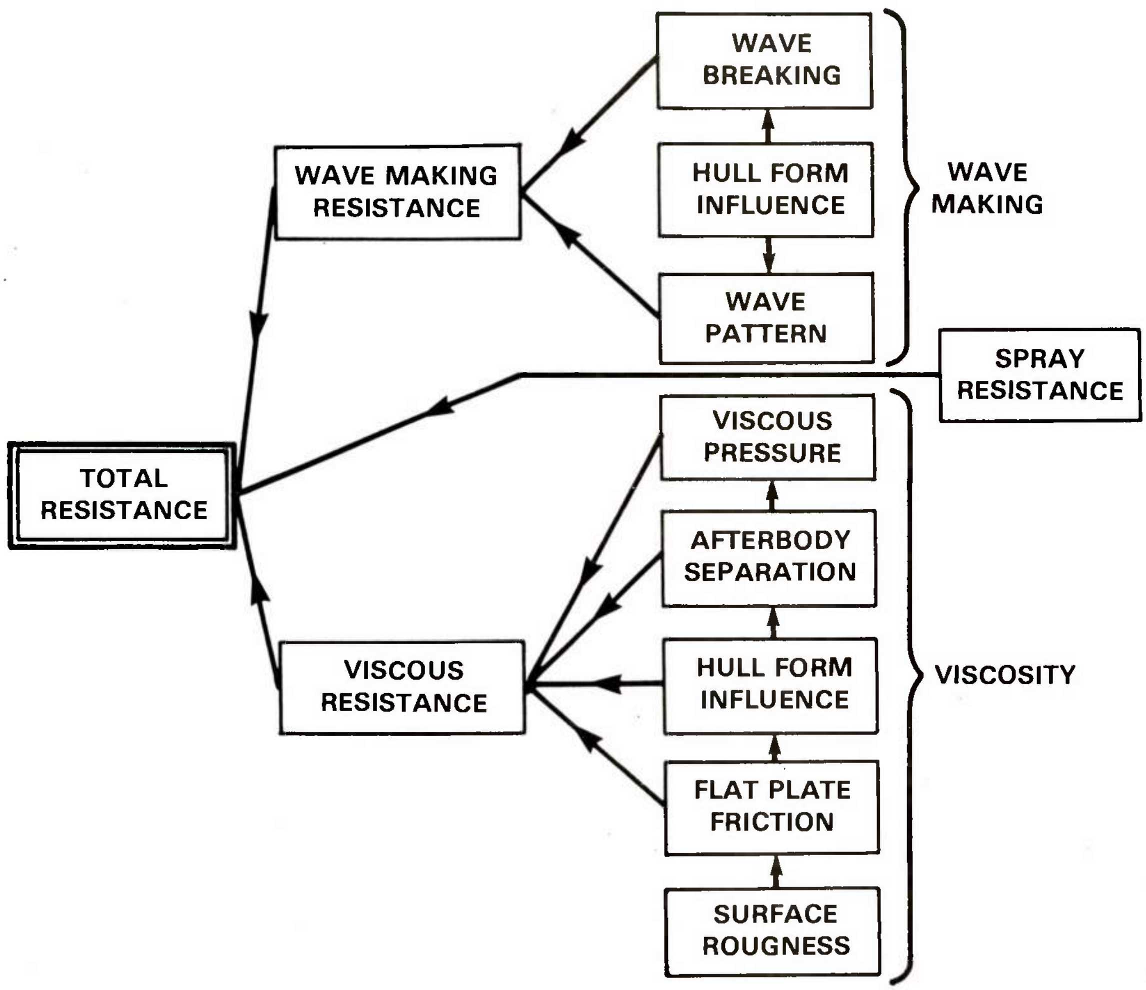


Figure 17 - Components of Ship Resistance in Calm Water
(From Williams[8])

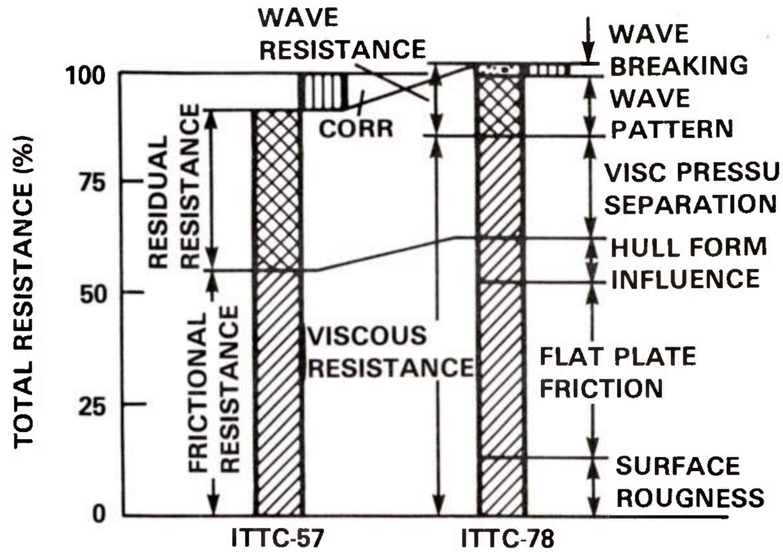


Figure 18a - 12,000-m^3 RO/RO at 18 Knots

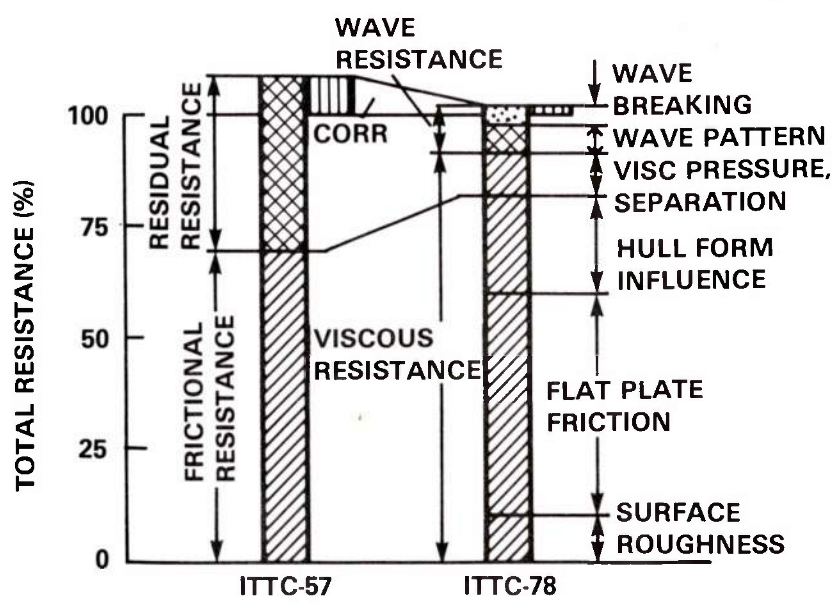


Figure 18b - 100,000-m^3 Tanker at 16 Knots

Figure 18 - Components of Ship Resistance, According to 1957 and 1978 International Towing Tank Conference Methods, for a RO/RO Vessel and a Tanker

(From Williams[8])

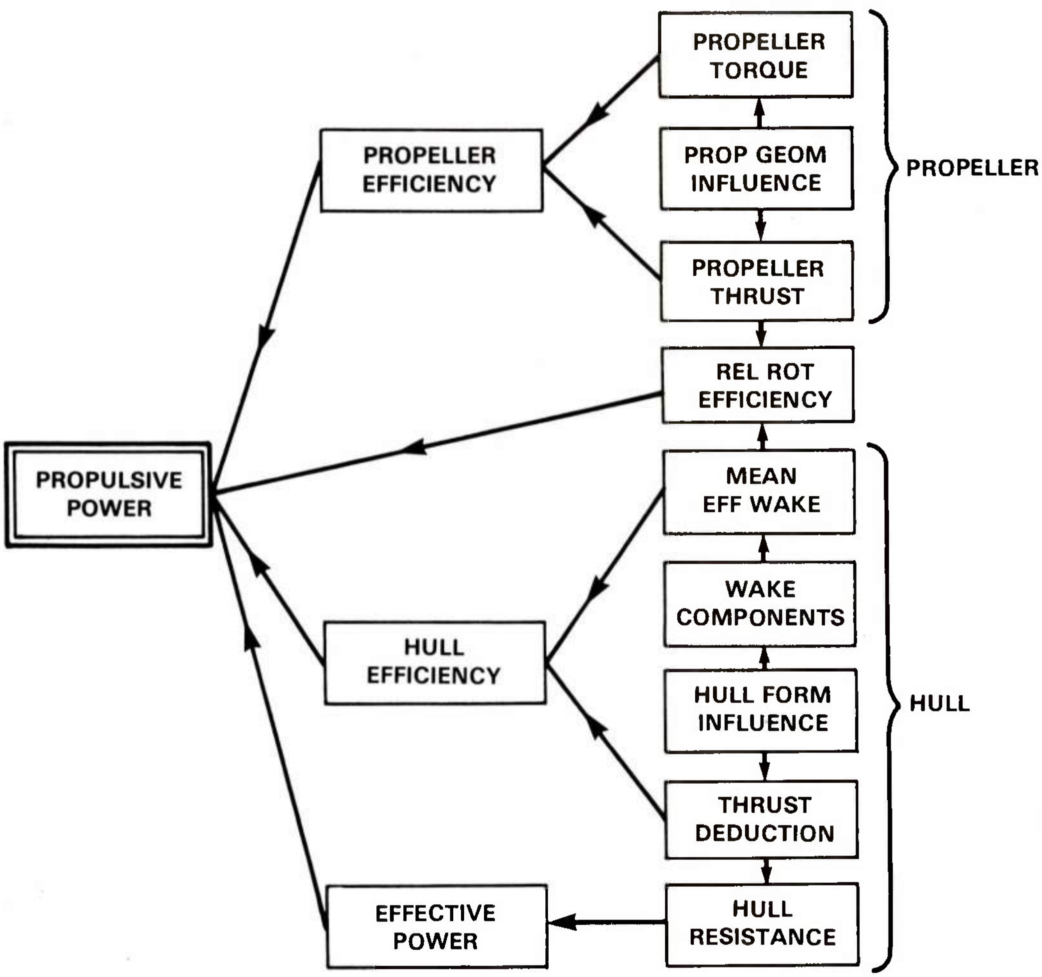


Figure 19 - Components of Propulsive Power
(From Williams[8])

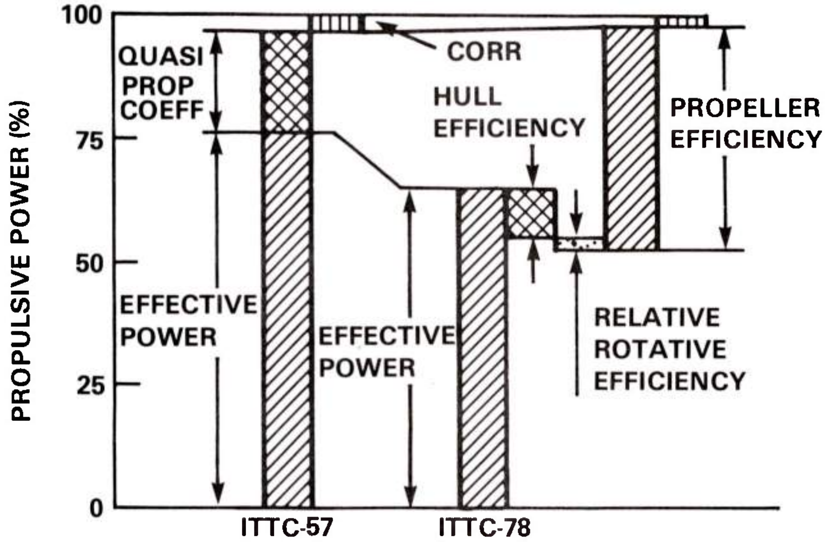


Figure 20a - 12,000-m^3 RO/RO at 18 Knots

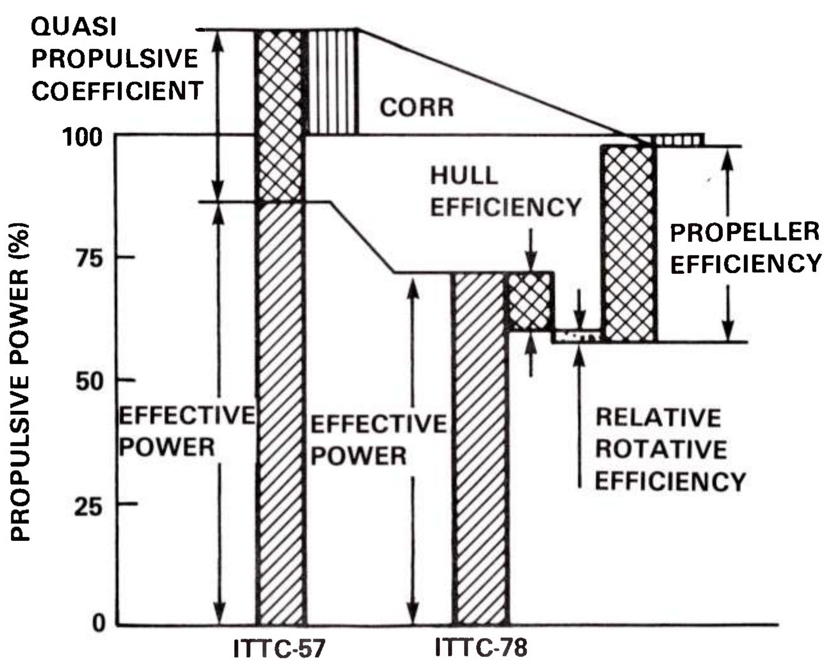


Figure 20b - 100,000-m^3 Tanker at 16 Knots

Figure 20 - Components of Propulsive Power, According to 1957 and 1978 International Towing Tank Conference Methods, for a RO/RO Vessel and a Tanker

(From Williams[8])

It is obvious from Figure 20 that the RO/RO vessel has a rather high hull efficiency (made up by effective mean wake and thrust deduction factor) in spite of its finer hull. For the RO/RO vessel as well as for the tanker the effective power has to be substantially increased due to the rather low propeller efficiency. This is, of course, an old and important problem in a shipboard energy saving program.

HULL FORMS

When the size of ships, especially tankers and bulkers, began to be drastically increased, one question was how far the conventional hull forms could be used. Regarding the afterbody hull form, a number or approaches have been made to "new" forms. To the common V- and U-formed afterbodies the bulbous stern afterbody (Figures 21, 22, and 23) has been added. These hull forms have been the subject of extensive investigations on propulsion and propeller cavitation by Dyne[9] at SSPA.

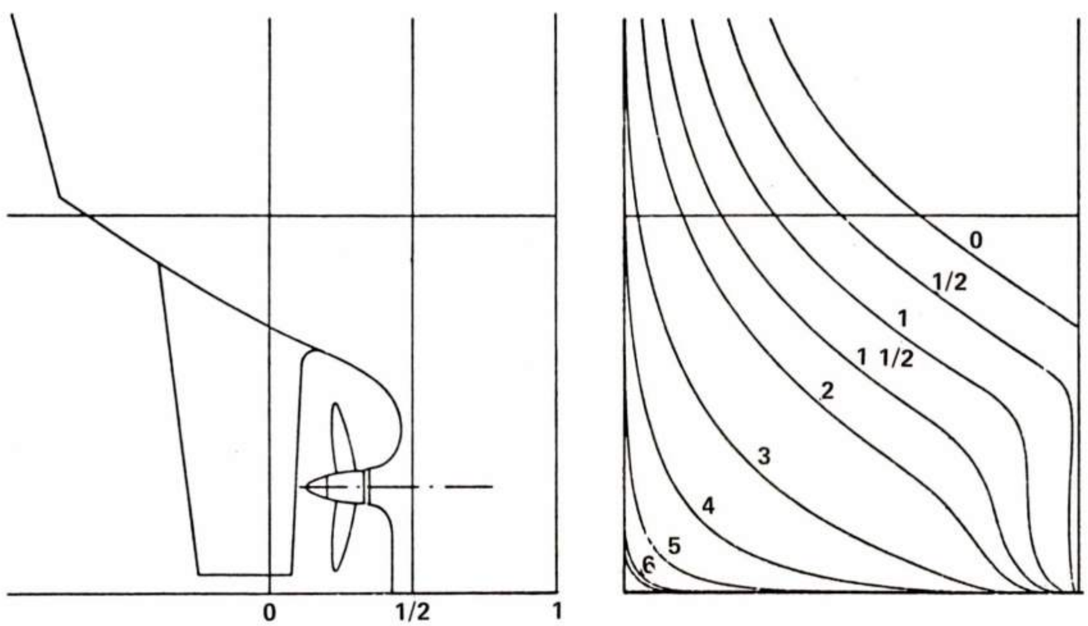


Figure 21 - Hull Forms for VLCCS/ULCCS (Very Large and Ultra Large Crude Carrier Ships) with V-Shaped Afterbody
(From Williams[7])

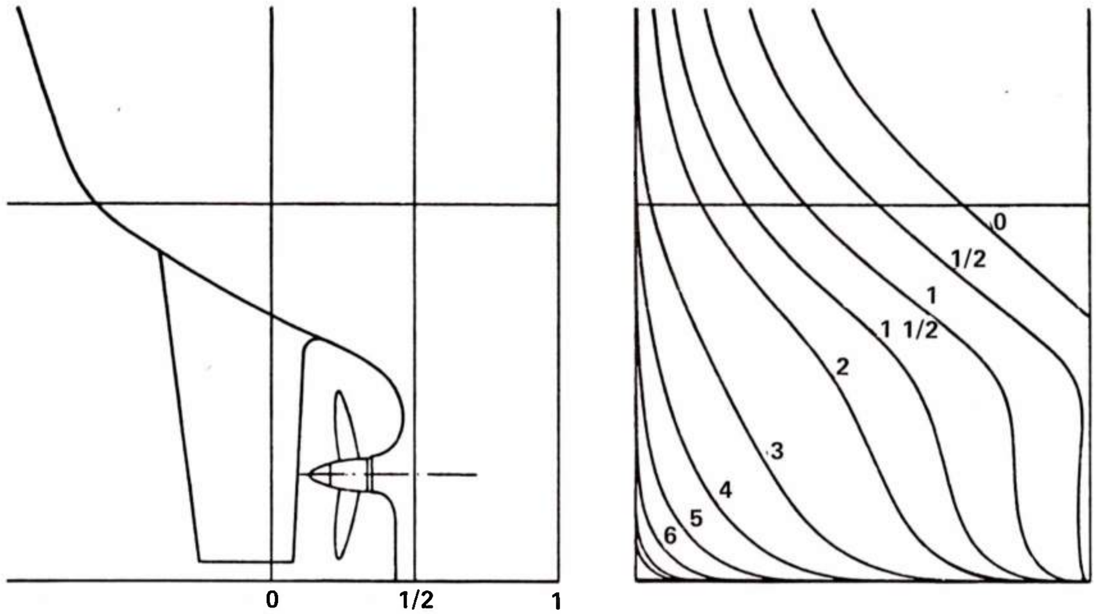


Figure 22 - Hull Forms for VLCCS/ULCCS with U-Shaped Afterbody

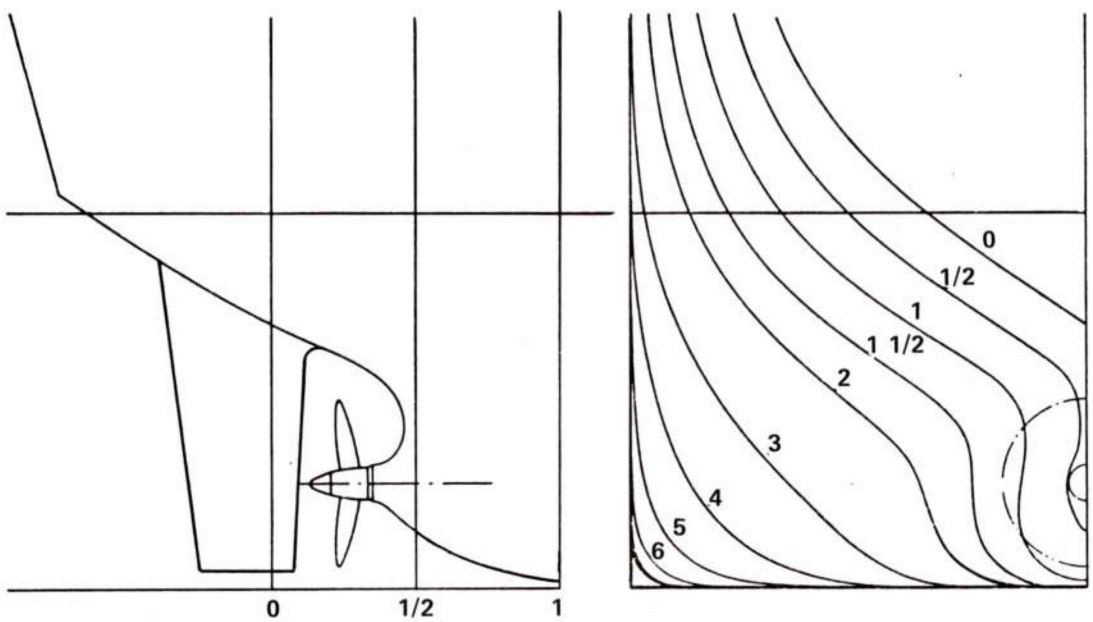


Figure 23 - Hull Forms for VLCCS/ULCCS with Bulbous Stern
(From Williams[7])

An interesting alternative is the "free-propeller" afterbody (Figure 24). For the twin-screw propulsion there are two alternatives: the conventional (Figure 25), and the twin-skeg or twin gondola (Figure 26). For restricted draft, skeg afterbodies or barge afterbodies can also be advantageous.

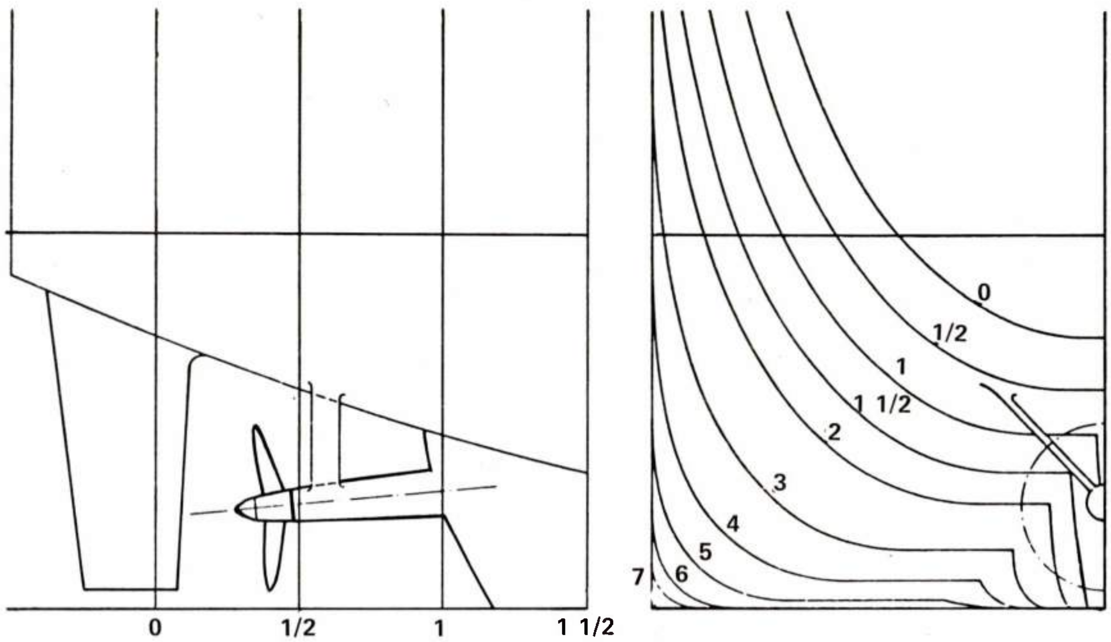


Figure 24 - Hull Forms for VLCCS/ULCCS with Free-Propeller Afterbody (From Williams[7])

Returning for a moment to the 12,000-m^3 displacement RO/RO vessel discussed above, the following can be said. The single screw RO/RO with conventional afterbody (Figure 27), will have difficulties both regarding longitudinal center of buoyancy (LCB) requirements and the demand for good wake distribution. This is, of course, especially so for short, full, and beamy ships, which are just the characteristics of many modern medium-sized RO/RO's. If the one-propeller concept is to be used at all, the skeg or free-propeller barge afterbody (Figures 28 and 29) is recommended.

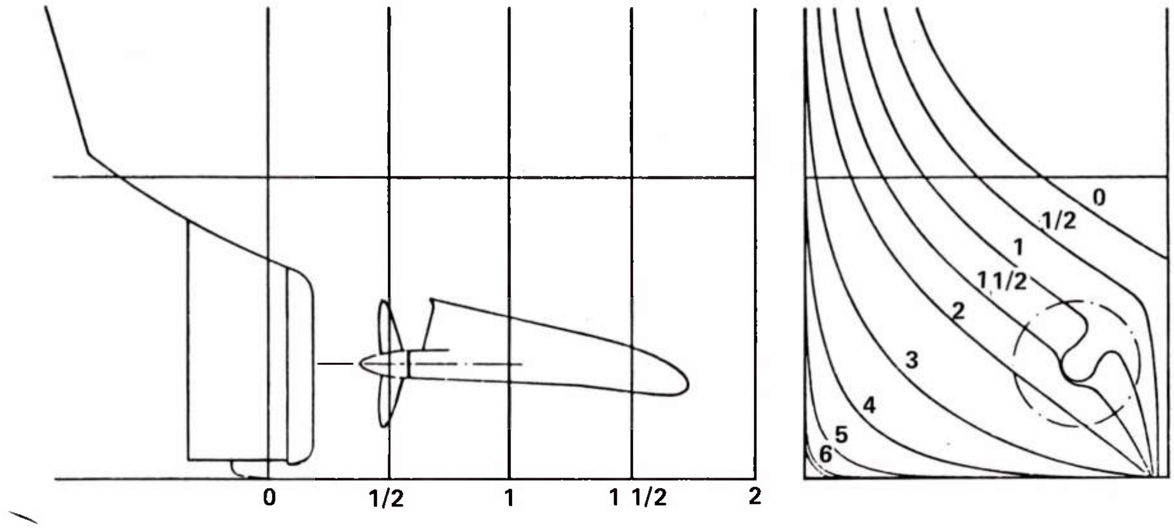


Figure 25 - Hull Forms for VLCCS/ULCCS with Conventional Twin-Screw Afterbody

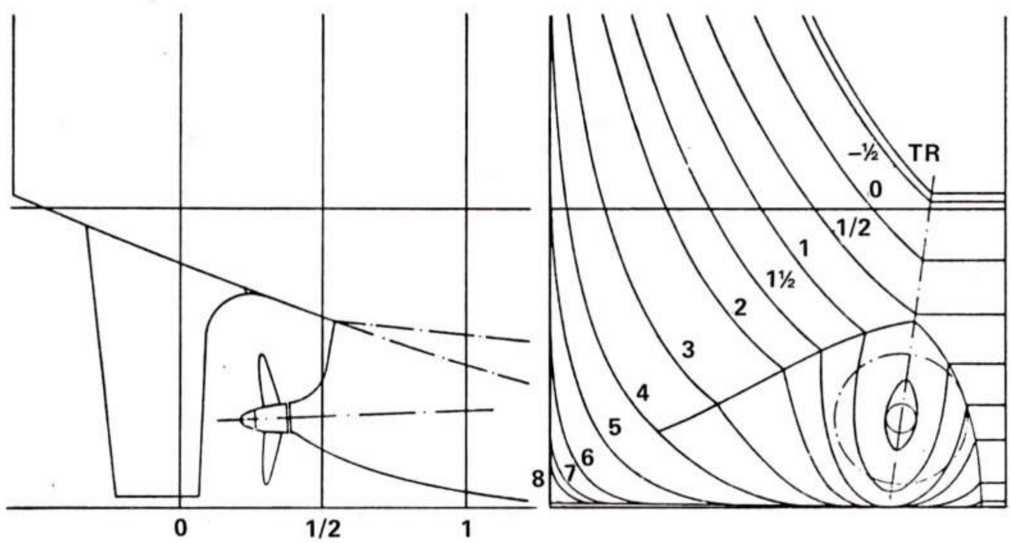


Figure 26 - Hull Froms for VLCCS/ULCCS with Twin-Screw Twin-Skeg Afterbody
(From Williams[7])

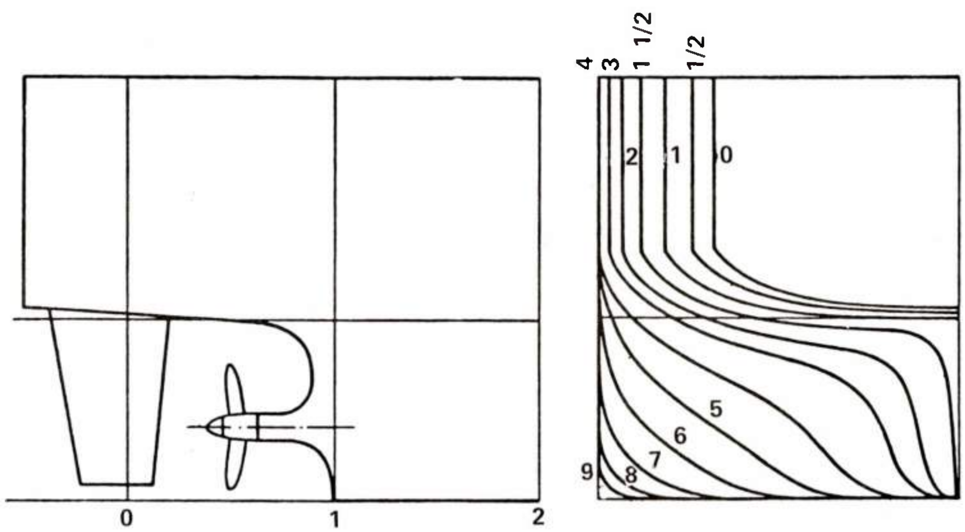


Figure 27 - Single-Screw RO/RO Vessel with Conventional Afterbody

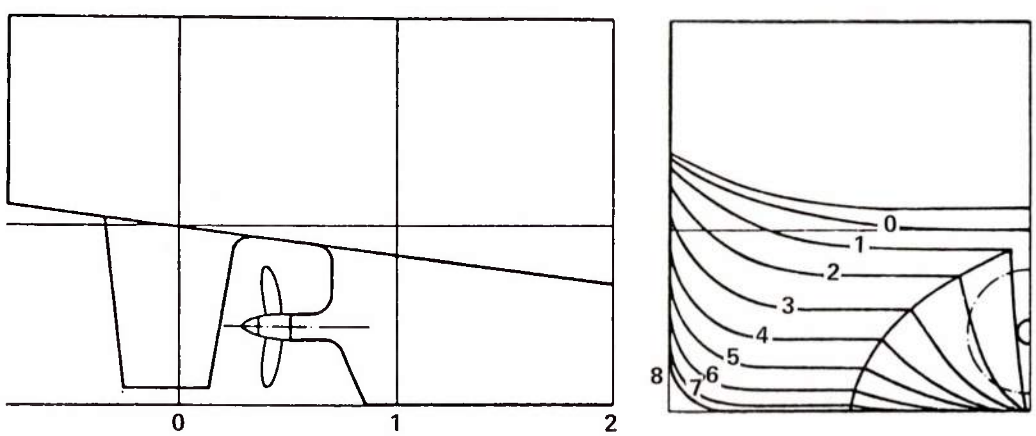


Figure 28 - Single-Screw RO/RO Vessel with Single-Skeg Afterbody

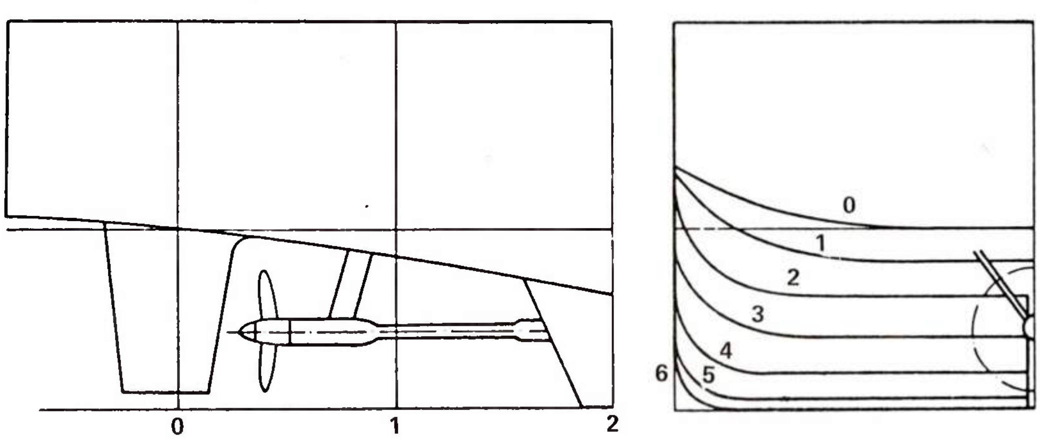


Figure 29 - Single-Screw RO/RO Vessel with Free-Propeller Barge Afterbody (From Williams[8])

The twin-screw concept may be preferable in many instances. The conventional V-formed afterbody with propeller as shown in Figure 30 is predominant. However, the twin-skeg (or twin-gondola) alternative is far better from a fuel consumption point of view (Figure 31). An extremely aft location of center of buoyancy (heavy loading gear far aft) may lead to a free-propeller barge afterbody (Figure 32). In Figures 33, 34, and 35 various forebody alternatives are shown. All with extreme V-form for large deck areas and waterlines at moderate fullness at design waterline (DWL) and below. The large bulbous bow can be used only if draft deviation from the design waterline can be kept small.

For the 100,000-m^3-displacement tanker discussed above, the single-screw alternative is most common. The engine power is also moderate in relation to the size of the ship. This, however, does not exclude the risk for afterbody vibrations. If, for some reason, a very high hull fullness has to be accepted, propeller-induced vibrations will be almost unavoidable for an ordinary single-screw ship.

The normal single-screw tanker has a U-formed afterbody (Figure 36). The skeg alternative (Figure 37) gives better wake field and reduced power requirements. The free-propeller afterbody (Figure 38) reduces shaft horsepower requirements even more, as well as reducing vibrations, if any, but it also takes more space for main engine room, which can be very expensive. Figures 39, 40, and 41 give alternative forebody forms for the 100,000-m^3-displacement tanker. If the forward draft is varied much, the forebody with sharp stem and without bulbous bow may be the best alternative, provided it is properly designed. At "slow steaming" the bulbous bow will almost certainly do more harm than good as far as fuel savings are concerned.

The hull forms referred to above are considered good according to the present standard at SSPA. However, the search for new ship hull forms is steadily going on. New, more specialized ship designs make new forms necessary.

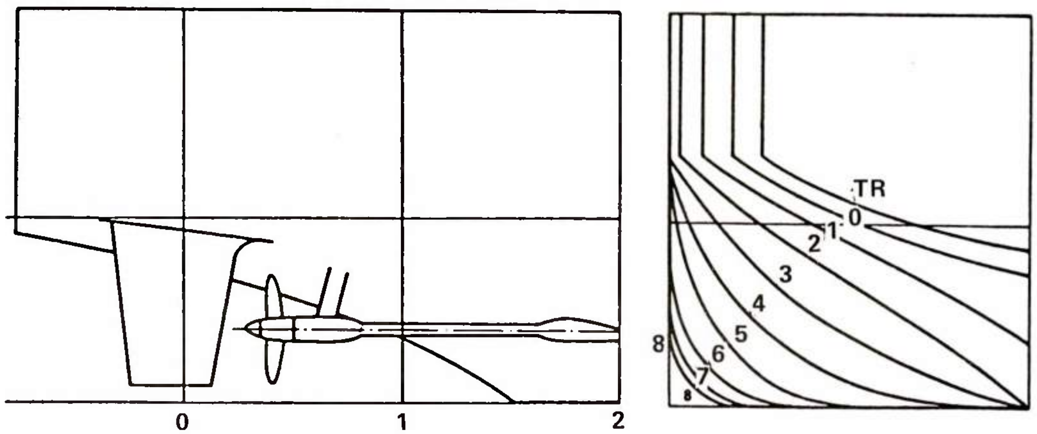


Figure 30 - Twin-Screw RO/RO Vessel with Conventional Afterbody

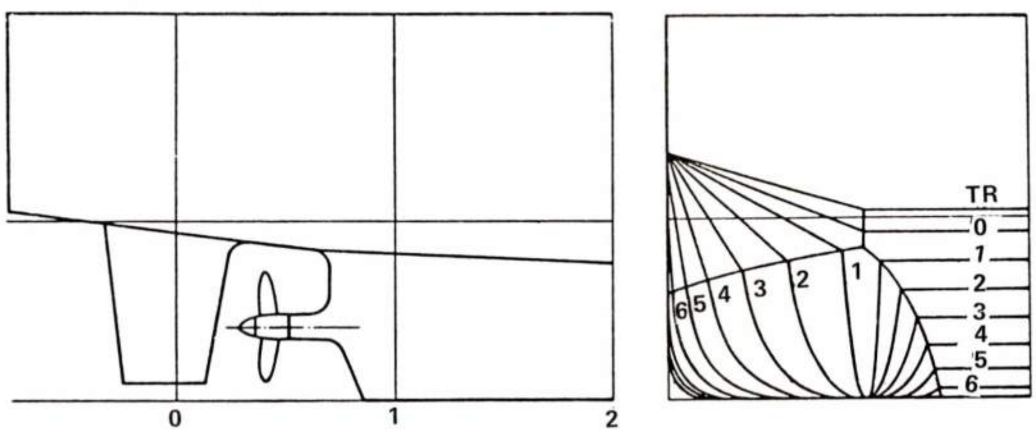


Figure 31 - Twin-Screw RO/RO Vessel with Twin-Skeg Afterbody

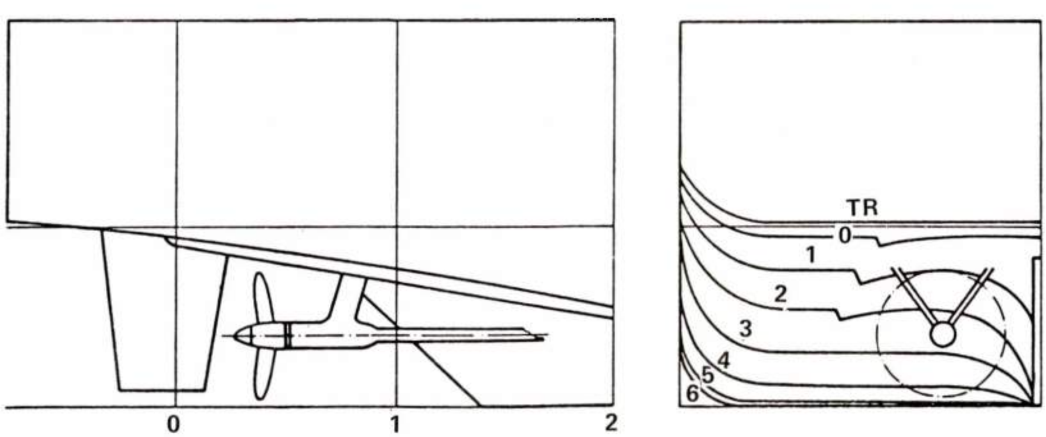


Figure 32 - Twin-Screw RO/RO Vessel with Free-Propeller Barge Afterbody (From Williams[8])

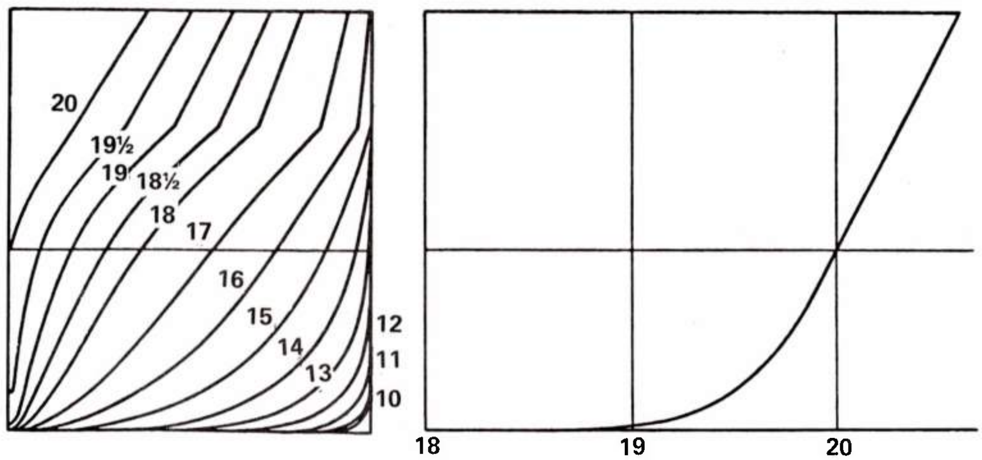


Figure 33 - RO/RO Vessel Having Forebody without Bulbous Bow

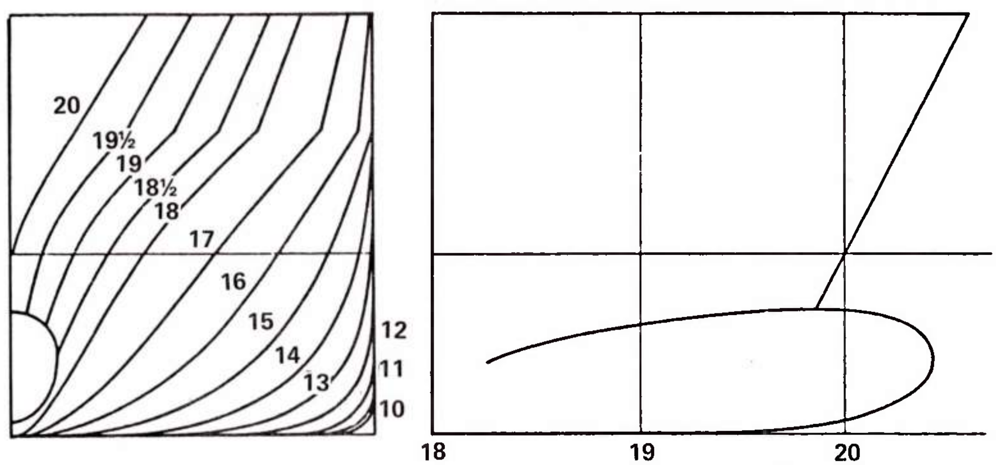


Figure 34 - RO/RO Vessel Having Forebody with Small Bulbous Bow

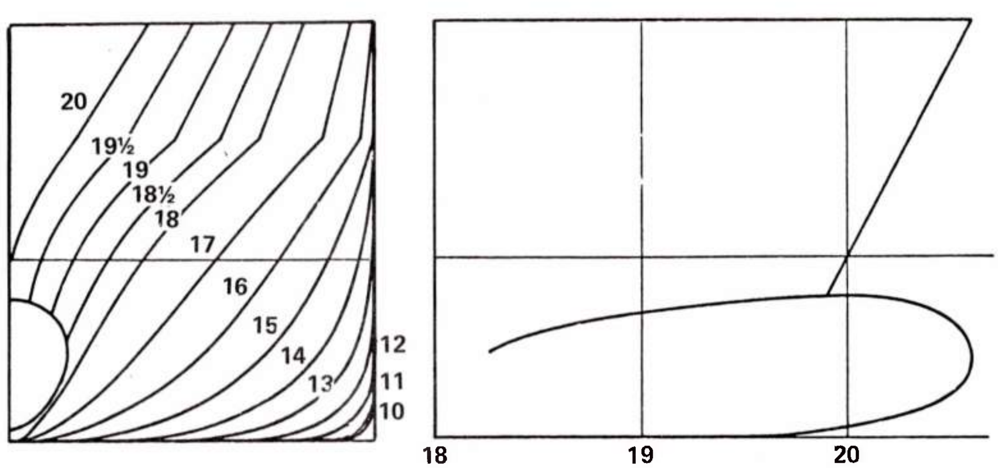


Figure 35 - RO/RO Vessel Having Forebody with Large Bulbous Bow (From Williams[8])

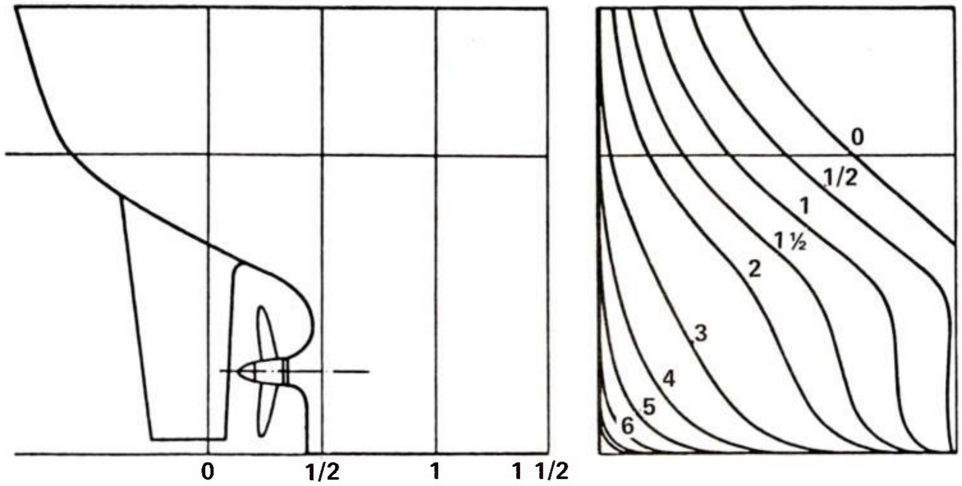


Figure 36 - Single-Screw Tanker with U-Formed Afterbody

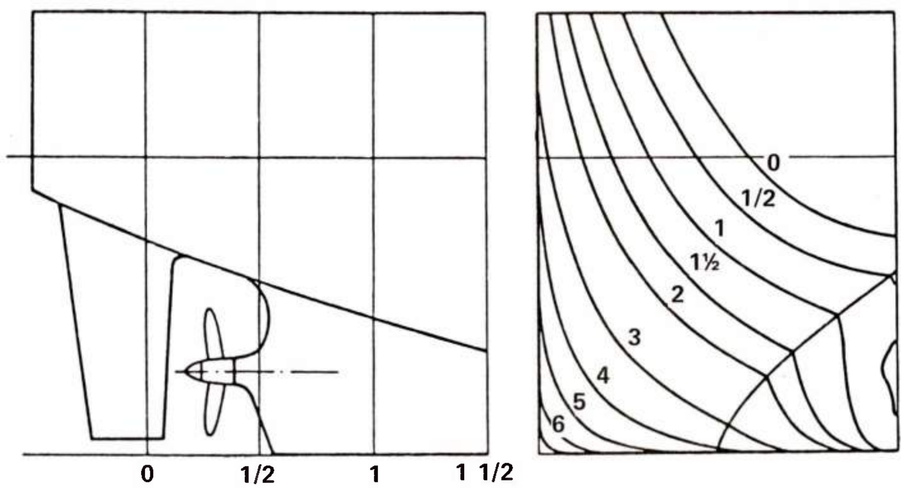


Figure 37 - Single-Screw Tanker with Skeg Afterbody

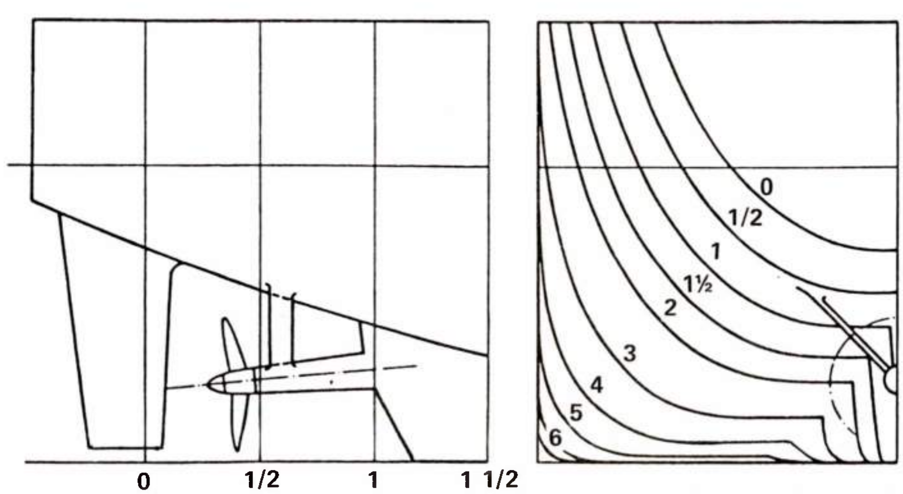


Figure 38 - Single-Screw Tanker with Free-Propeller Afterbody

(From Williams[8])

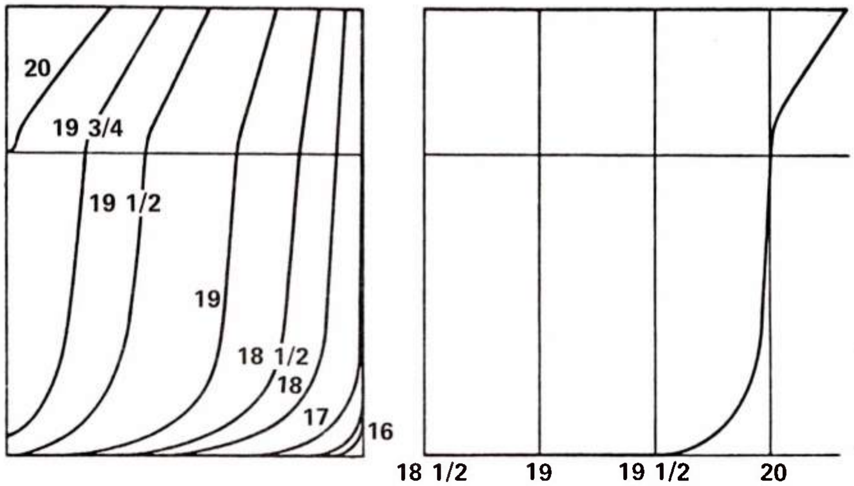


Figure 39 - Tanker Having Forebody without Bulbous Bow

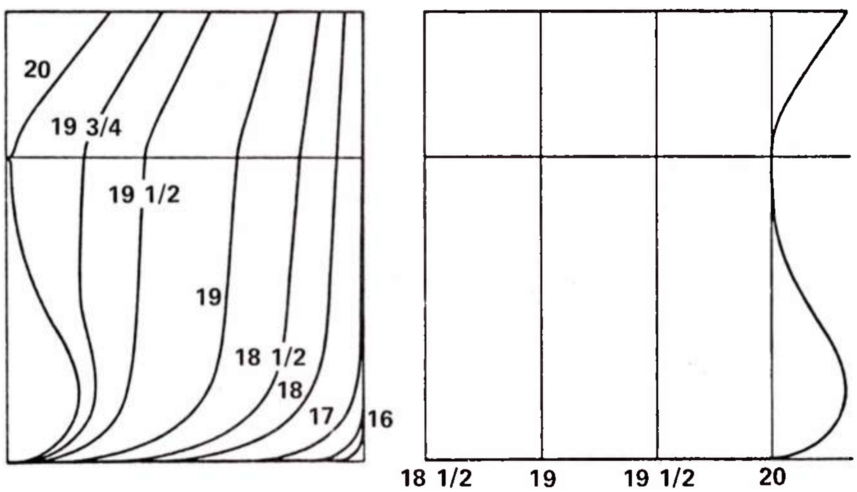


Figure 40 - Tanker Having Forebody with Bulbous Bow

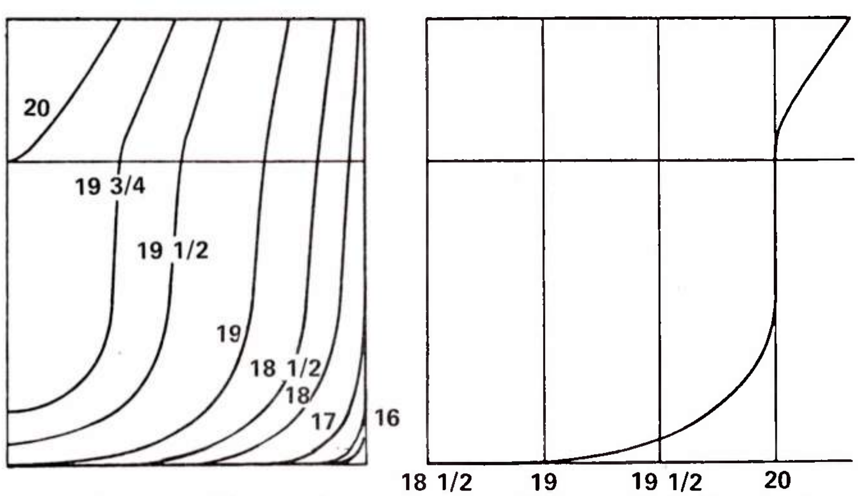


Figure 41 - Tanker Having Ellipsoidal Forebody

(From Williams[8])

LECTURE IV

PROPELLER CAVITATION AND EROSION

INTRODUCTION

The rapid increase in size, speed, and engine power of ships has generally made avoiding propeller cavitation difficult. The water flow behind and close to the afterbody, strongly disturbed in velocity and direction, together with disturbances in the form of separation phenomena from the hull itself, make it problematic to design propellers which are acceptable from vibration and erosion points of view. A thorough knowledge of the interaction effect among hull, propeller, and rudder is required. At very high speeds, for example for torpedo boats, highspeed hydrofoil vessels, etc., extensive cavitation has had to be accepted on load bearing surfaces, such as planing parts of the hull, hydrofoils and propeller blades, supercavitating surfaces. The design and construction of supercavitating propellers or hydrofoils require a special technique.

To avoid, or at least reduce, the detrimental effects of cavitation and to master the problems connected with supercavitating surfaces, intensive research is going on throughout the world. This research is carried out along two lines. One is basic research, i.e., the study of cavitation from a physical, hydrodynamic, and thermodynamic point of view; the other is applied research, which means the study of the cavitation phenomenon and its effects on propeller models or other test objects. The applied research takes place in cavitation laboratories.

VARIOUS TYPES OF CAVITATION LABORATORIES

As with all model investigations, propeller cavitation tests must be carried out under conditions as realistic as possible; for example, the wake field must be realistically reproduced. However, certain approximations are necessary to keep the investments in facilities and thus the costs for tests within reasonable limits. Different judgements have led to different compromises in this respect, the result being the following types of facilities:

1. Conventional cavitation tunnel, the wake field being established by the use of afterbody models (or parts of afterbody models) in combination with nets. This is the most common solution.

2. Cavitation tunnel having a test section long and wide enough to allow complete ship models to be used for establishing the wake field, one example being the large tunnel at SSPA, Gothenburg.
3. Facilities including a free surface. Examples are the large circulating tunnel at Versuchsanstalt für Wasserbau und Schiffbau (VWS), West Berlin, and the depressurized towing tanks at Netherlands Ship Model Basin (NSMB), Wageningen, and at Kryloff Ship Research Institute, Leningrad.

The second facility type listed above can be regarded as a development and an improvement of the first. The main advantages with a large tunnel and a complete ship model are the following:

a. If the geometry of the ship is correctly reproduced, more accurate values of the pressure fluctuations can be expected (correct solid boundary factors).
b. If the wake field is created entirely by the hull without contributions from nets, the important interference between propeller and hull is more likely to be correctly reproduced.
c. If the tests using afterbody models are carried out in test sections having rather small dimensions, the levels of the signals may be affected by reflections in the walls. This interference is less likely in a larger tunnel.

Comparisons between observations of model propeller cavitation in the large tunnel at SSPA and the corresponding results from full scale observations show good agreement. Also, pressure fluctuations measured on models in the large tunnel agree very well with those from full scale measurements. A rather extensive comparison between results from the large SSPA tunnel and the depressurized towing tank at NSMB, carried out for a tanker project, shows good agreement between the two facilities.

The advantages of incorporating a free water surface, as in a depressurized towing tank, are the following:

a. The wake distribution will be better reproduced than in a facility without free surface, because the effects of the afterbody wave system are taken into account. These effects have, however, been proven to be very small, for fast container ships as well.

b. Investigations of extreme ballast cases in which the propeller is close to the water surface are difficult to carry out in a facility without free surface.

The disadvantages of incorporating a free water surface, however, are the following:

a. The presence of a free surface fixes the speed of the model in accordance with Froude's law at rather low velocities (1-3 m/s). This means that, in order to establish a correct cavitation number, very low static pressures are necessary in most cases. These low pressures, in combination with a large free surface, cause great difficulties in establishing enough gas nuclei to create cavitation at pressures corresponding to full scale. To overcome these difficulties gas nuclei have to be produced artificially, for example by electrolysis.

b. The limitation of velocity means low Reynolds numbers, but a high Reynolds number is an important condition for obtaining cavitation patterns corresponding to full scale. This problem has been partly overcome at NSMB by use of larger ship models than are normally used in towing tanks (12 m compared to 7-8 m at SSPA).

c. The time for observations is much more limited in a depressurized towing tank than in a circulating water tunnel.

THE DEVELOPMENT IN SWEDEN

The first cavitation tunnel for ship propellers was built in 1941 at Kamewa at Kristinehamn (Figure 42). Kamewa, a manufacturer of controllable pitch propellers, belongs to KMW, a water turbine manufacturer. They had a cavitation tunnel for water turbines in 1920. The propeller tunnel has a square test section (800 mm × 800 mm) with rounded corners. The maximum water speed is 9 m/s with 150 hp impeller. The downstream bend after the test section is divided in two branches and the model propeller shaft goes out downstream in the space between these two branches. The tunnel, still in operation, is now at the Danish tank at Lyngby. Kamewa now has two propeller cavitation tunnels in operation at Kristinehamn, one of them has a free water surface.

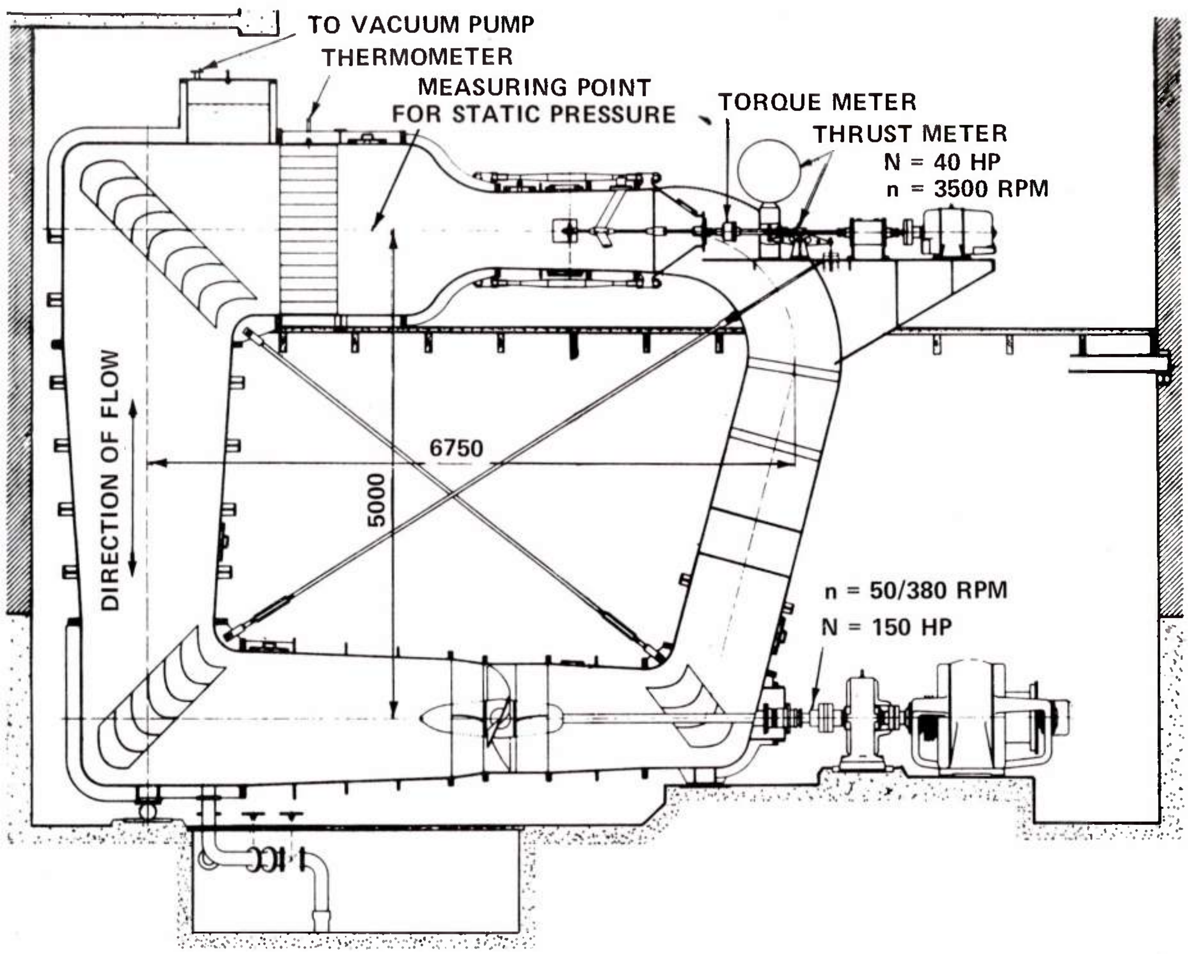


Figure 42 - The Two-Storey Vertical Cavitation Tank for Ships' Propellers at K.M.W. in Kristinehamn. In the Smaller Section in the Upper Part's the Model Propeller; to the Right of This is the Shelf for the Measuring Apparatus and the Driving Motor. The Water Motion (Clockwise) is Produced by the Propeller-Pump in the Lower Part, and Can Reach a Maximum Speed of 9 m/s Through the Measuring Section. By Reducing the Air in the Dome (to the Left of the Upper Part) by Means of an Air Pump One Can Obtain Different Pressures in the Tank and Thereby Different Cavitation Conditions at the Model Propeller.

(From Edstrand[11])

Around 1950 a very large cavitation tunnel with free water surface was under consideration at SSPA. It was planned to be of about the same size as the circulating water tunnel at DTNSRDC. However, this idea was soon abandoned due to the enormous investment costs involved.

In 1957 a cavitation tunnel was opened at SSPA (shown earlier in Figure 5). In this tunnel the concept of interchangeable test sections was first introduced. Two test sections with the dimensions 0.5 m × 0.5 m and 0.7 m × 0.7 m were used. The maximum water speeds are 11 m/s and 7 m/s, respectively. One important purpose of this tunnel was to use it as a scale model to establish empirically technical data for the design of a larger cavitation laboratory.

The "dummy model technique" was introduced by SSPA in this tunnel. The large test section (0.7 m × 0.7 m) was usd for this purpose. This section is 2.4 m long, and the wake distribution is simulated by a ship afterbody model combined with wake producing nets.

The large cavitation tunnel at SSPA was ready in 1969 (see Figure 6). Like the older one, this one has two interchangeable test sections. The large test section is rectangular with a breadth of 2.6 m, a height of 1.5 m and a length of about 10 m. In this section a complete 7-8-m-long ship model, identical to the one used in the towing tank, creates the wake. The section is covered by a recess in which the ship model is placed. The vertical position of the model is adjusted so that the waterline, corresponding to the level of the free water surface in the towing tank, is flush with the top of the test section. Individually cut wooden plates are then fitted to simulate the free water surface and the test section and recess are filled completely with water. The maximum water speed in this test section is 6.8 m/s, the minimum cavitation number $\sigma = 1.0$.

The smaller of the test sections is circular and has a diameter of 1 m. The maximum water speed is 23.6 m/s. Theoretically the section can work down to absolute vacuum and can stand an overpressure of 5 atmospheres. This section is used for tests of partially and totally cavitating model propellers in axial or nonaxial flow. Moreover, it is used for experiments with bodies of revolution making it possible to carry out measurements of pressure distributions, resistance, and stability derivatives. Also, lifting force and resistance on profiles can be measured; special flow investigations such as studies of appendages and multipropeller arrangements for fast ships can be done; and experiments with completely cavitating and ventilated hydrofoils can be carried out.

Work done in this tunnel has included basic studies of cavitation phenomena, flow visualization, and cavitation noise. Great efforts have been devoted to calibrating the tunnel. This required, among other things, extensive comparisons between model tsts and the corresponding full scale results as regards cavitation pattern observations, cavitation erosion, propeller-excited vibratory forces, and propulsive performances.

The possibility of working with two test sections rationalizes the operation and increases the degree of utilization of the installations. Test rigs and test objects can be fitted in one test section while tests are going on in the other. Two specially designed cranes, each with a lifting capacity of 20 tons, facilitate quick exchange of the test sections.

After 12 years of commercial tests and research, the tunnel has proved to be a most useful tool for all kinds of cavitation investigations.

GAS AND NUCLEI PROBLEMS

Also even in a cavitation tunnel that accurately models the wake field by the method described above, there can be differences in measured values between model and full scale. Physical and chemical properties of the water, for instance, can cause such discrepancies. Gas separation, which takes place in the water at reduced pressure, has this effect. The design of the conventional cavitation tunnel and the experimental technique involved do not guarantee correct gas separation ahead of and within the model propeller in comparison with that relating to ship conditions.

Numachi and Kurokawa[12] many years ago investigated cavitation and gas separation in water flowing through small glass nozzles (Figure 43). They used distilled water, natural seawater and synthetic seawater made from pure salt and distilled water. They measured the cavitation pressure, i.e., the pressure at which cavitation or gas separation in the nozzle first became visible with water of various gas contents. They found that gas content had a very large influence on the critical pressure. They also found a very large difference between results in distilled and seawater.

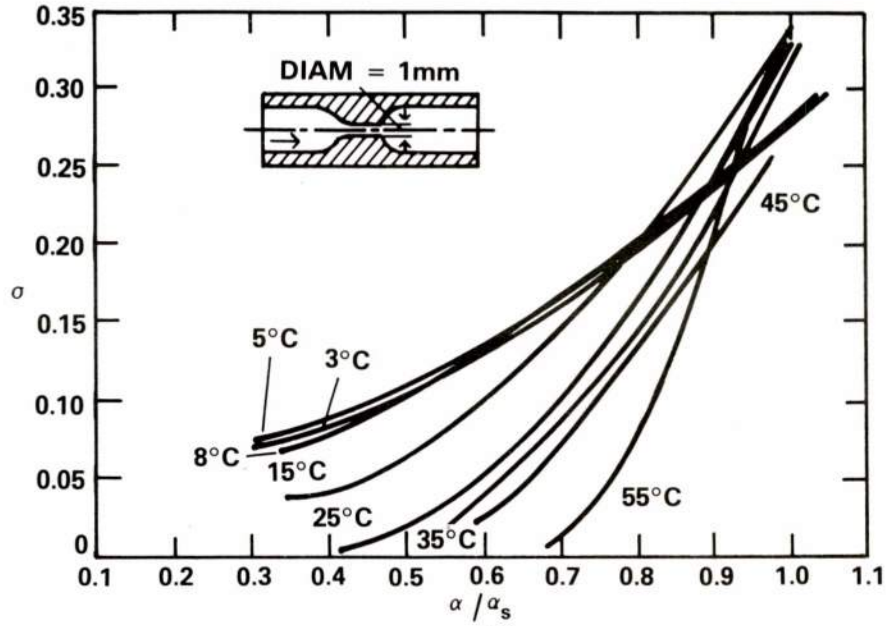


Figure 43 - Cavitation Index $\sigma = \frac{p_o - e}{q_o}$ as a Function of the Relative Air Content $\frac{a}{a_s}$. The Curves Give the Cavitation Point Observed in a Glass Nozzle with 1 mm Cross Section at Different Water Temperatures. (From Edstrand[11])

In the late 1940's I carried out an extensive investigation of the influence on propeller characteristics of the gas content of tapwater and natural seawater. These investigations were carried out in the Kamewa cavitation tunnel at Kristinehamn (Figure 44). All results from this investigation have been published in the SSPA Publication Series. Briefly, the gas content of the cavitation tunnel water has a considerable influence on incipient cavitation and on propeller characteristics, particularly when the cavitation appears as bubble cavitation. Also, this influence is magnified in seawater compared with tapwater. Seawater certainly contains more solid particles, which serve as nuclei for cavitation.

Oxygen and nitrogen and also argon, which is usually included with the nitrogen, are dissolved in water at constant molecular weight. Thus, they do not react chemically with the liquid and the solution follows Henry's law, i.e., the quantity of gas dissolved is in direct proportion to the partial pressure which each gas exerts

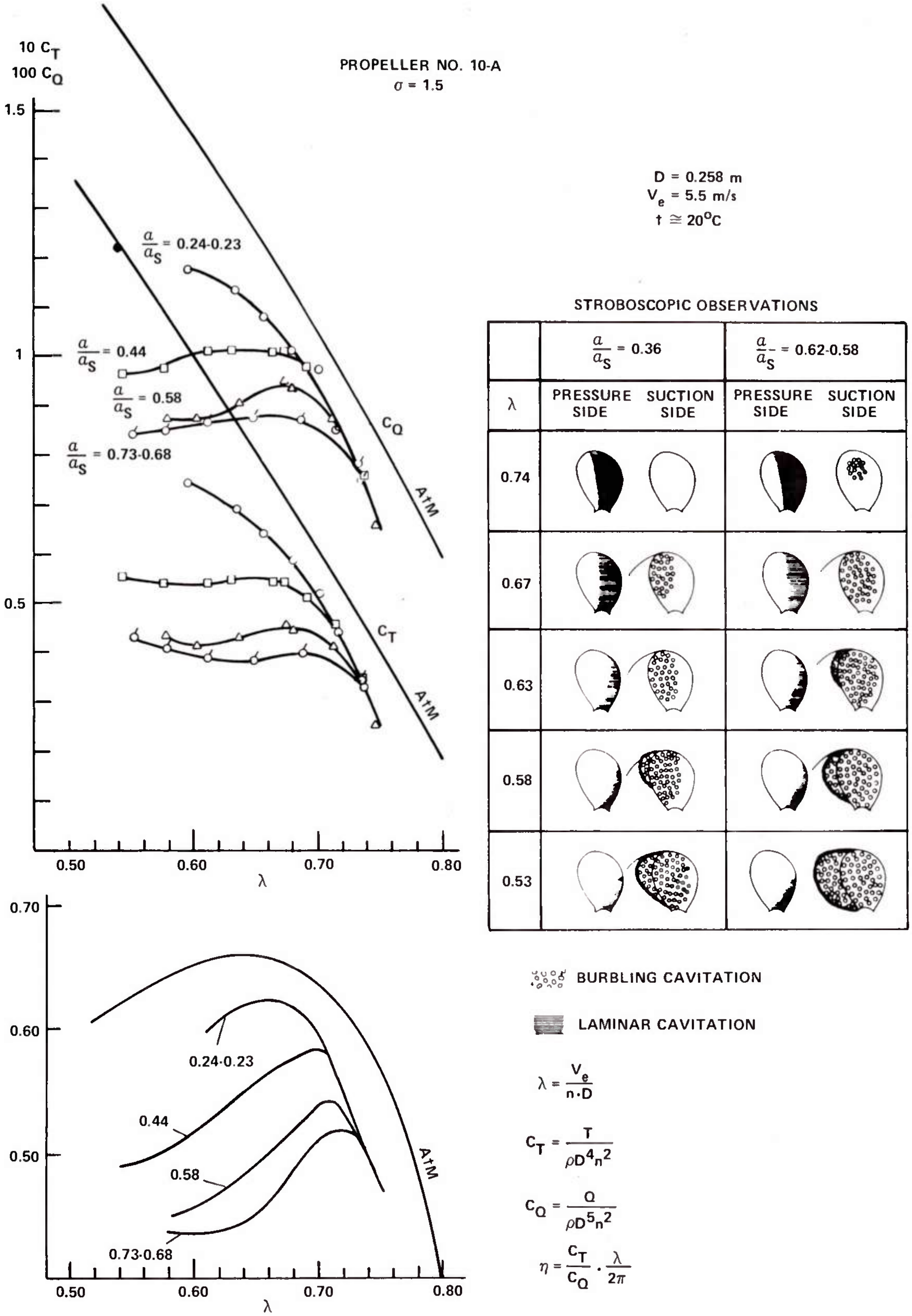


Figure 44 - Influence of Gas Content on Propeller Characteristics (From Edstrand[11])

upon the surface of the liquid. The solubility of oxygen in distilled water is about twice that of argon-free nitrogen. Since, however, atmospheric air is composed of about 4/5 nitrogen and 1/5 oxygen, water in equilibrium with the outside atmosphere contains dissolved oxygen and nitrogen approximately in the proportions of 1:2 in accordance with Henry's law (Figure 45).

For seawater the situation is complicated because of the carbon dioxide system. Seawater contains CO_2, part of which is free in the form of dissolved gas and part fixed in the form of carbonate and bicarbonate ions. Besides free CO_2, seawater also contains a small amount of undissociated H_2CO_3. This part, however, is very small and is therefore usually included with the free CO_2. All these components of the carbon dioxide system are in equilibrium with one another. In short, it might be said that this system creates a CO_2 reserve in seawater when the pressure is decreasing and consequently the water degasing. As a result, the amount of free dissolved CO_2 will increase in proportion to the oxygen and nitrogen when seawater is degasing.

The aforementioned properties of atmospheric gases dissolved in water are of great importance to testing techniques in cavitation tunnels. When the pressure is lowered during a cavitation test, oxygen and nitrogen are released in accordance with Henry's law, so that a new state of equilibrium results corresponding to the new pressure. This state of equilibrium is not determined, in any case not in cavitation tunnels of the conventional type, by the pressure which is exerted on the model propeller and which is chosen according to the pressure conditions required. Some of the gases which separate under the low pressure around the model propeller redissolve in other parts of the tunnel. Thus the state of equilibrium depends upon some mean pressure in the tunnel. Also, unavoidable leakage influences the gas content of the water in the tunnel. All the above mentioned properties of the cavitation tunnel, which depend upon its design and construction, are of great importance in evaluating the test results and comparing them with those for the ship. Every cavitation tunnel design has its own individual water gas balance.

Based on results of my investigation with tapwater and natural seawater in the cavitation tunnel at Kristinehamn referred to above, I proposed a new definition of

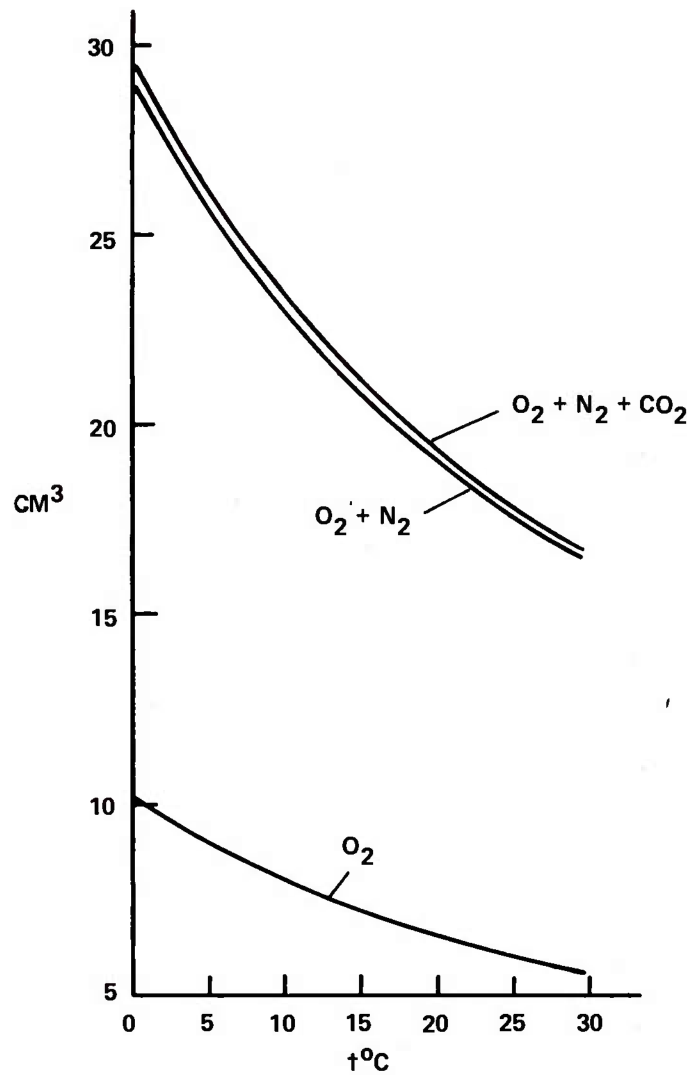


Figure 45 - The Amount of Dissolved Gas per Liter of Distilled Water at Atmospheric Pressure and Saturation Point Expressed as a Function of the Water Temperature. Gas Volumes are Reduced to 0° C and 760 mm Pressure
(From Edstrand[11])

the cavitation number. Instead of the vapor pressure I introduced the gas saturation pressure at the gas content concerned and a correction factor for this latter pressure. The correction factor depends upon the design of the cavitation tunnel and varies from one tunnel to another. This definition was introduced to the 6th International Conference of Ship Tank Superintendents in Washington, D.C., in 1951 and is described in its Proceedings.

SOME INVESTIGATIONS IN THE SSPA CAVITATION LABORATORY

In 1964 a proposal for comparative cavitation tests with a simple body of revolution was sent out by SSPA to a number of cavitation laboratories all over the world. At the International Towing Tank Conference (ITTC) in Tokyo 1966, the results from 14 establishments were presented and compared.

The test program primarily included the determination of incipient cavitation at different water velocities and gas contents. The test results obtained were quite alarming. The σ-value for incipient cavitation ranged from about 0.4 to 1.0 in different tunnels for tests at the same water speed and gas content. The results indicated, among other things, that the definition of the cavitation number with the vapor pressure was not enough to equate tests from cavitation tunnels of different designs.

To obtain some fundamental information concerning the noise generated by different kinds of cavitation, tests with a number of head forms and hydrofoils have been carried out at SSPA.[13] The aim was to get well-defined types of cavitation, i.e., bubble, sheet, and vortex cavitation. Comparisons were made among noise levels from these various types of cavitation, and the effects of free stream velocity and gas content were studied.

From the tests it can be concluded that in general, sheet cavitation produces substantially higher noise levels than vortex cavitation. Bubble cavitation produces the largest increases in noise level (Figure 46).

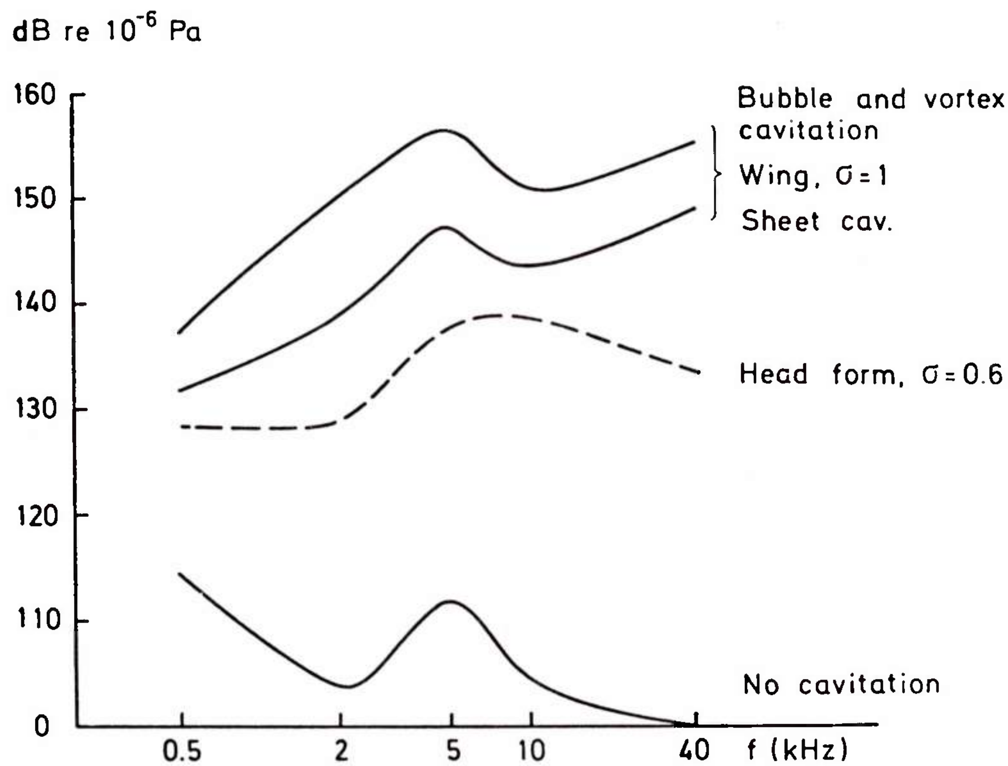


Figure 46 - Noise Levels Measured from a Cavitating Wing and A Cavitating Head Form

(From Lindgren and Bjärne[13])

The main purpose with the large cavitation tunnel at SSPA is, of course, studies of propeller cavitation. In the large test section these observations are combined with measurements of propeller-induced pressure pulses on the ship model hull surface.

The high speed test section is used mainly for propeller force measurements and cavitation studies in homogeneous flow with or without shaft inclination. Shaft brackets and boundary surfaces with possibilities of measuring pressure fluctuations can also be mounted at these tests. The cavitation tunnel is also an excellent tool for various types of flow studies and wake measurements.

The cavitation patterns on propellers in behind conditions are usually observed at propeller loadings corresponding to trial and service conditions defined by advance coefficient and cavitation number at the draughts of current interest. The trial case is based on the self-propulsion test results corrected for scale effects. The service case is deduced by use of the open water propeller characteristics, assuming roughness allowance on shaft horsepower and wake friction due to fouling.

The propeller cavitation extention and character at different blade positions are recorded with sketches and photographs. The maximum radial extension of the cavitation during one revolution is also presented. The cavitation is usually also recorded on videotape and can be analyzed in detail with the aid of a TV monitor. The stability of the cavitation can then be examined (Figure 47).

Experience has shown that cavitation formed by very small bubbles (foaming or cloud cavitation) is regarded as eroding and must therefore be avoided. This type of cavitation appears when bubble or sheet cavitation collapses on the propeller blade surface. The foaming cavitation appears, for instance, at the trailing edges on the back of the blade, when the blade leaves the wake peak behind the stern, at the leading edge on the face at the outer blade positions or at the blade root during tests with inclined propeller shaft. A procedure for determining possible cavitation erosion has been developed at SSPA. The propeller model is coated with a mixture of paint thinner and black stencil ink. The tests are carried out for 30 min at the topical propeller loading. If eroding cavitation of the type described above appears, the damage is indicated by the paint's being eroded away (Figure 48).

Variation in propeller induced pressure pulses on the hull surface is measured simultaneously by eight transducers or more around the propeller aperture. The transducers are cylinders with a diameter of 7 mm and they are mounted with the membrane flush with the hull surface (Figures 49 and 50).

The results of the pressure pulse measurements are related to those obtained at other tests (Figure 51). If, according to response criteria (Figure 52), unacceptable levels of pressure pulses are obtained, improvement of afterbody shape and/or propeller design are recommended. The results can also be integrated so that the vertical propeller-induced force acting on the afterbody, as well as its variation during a blade passage, can be determined.

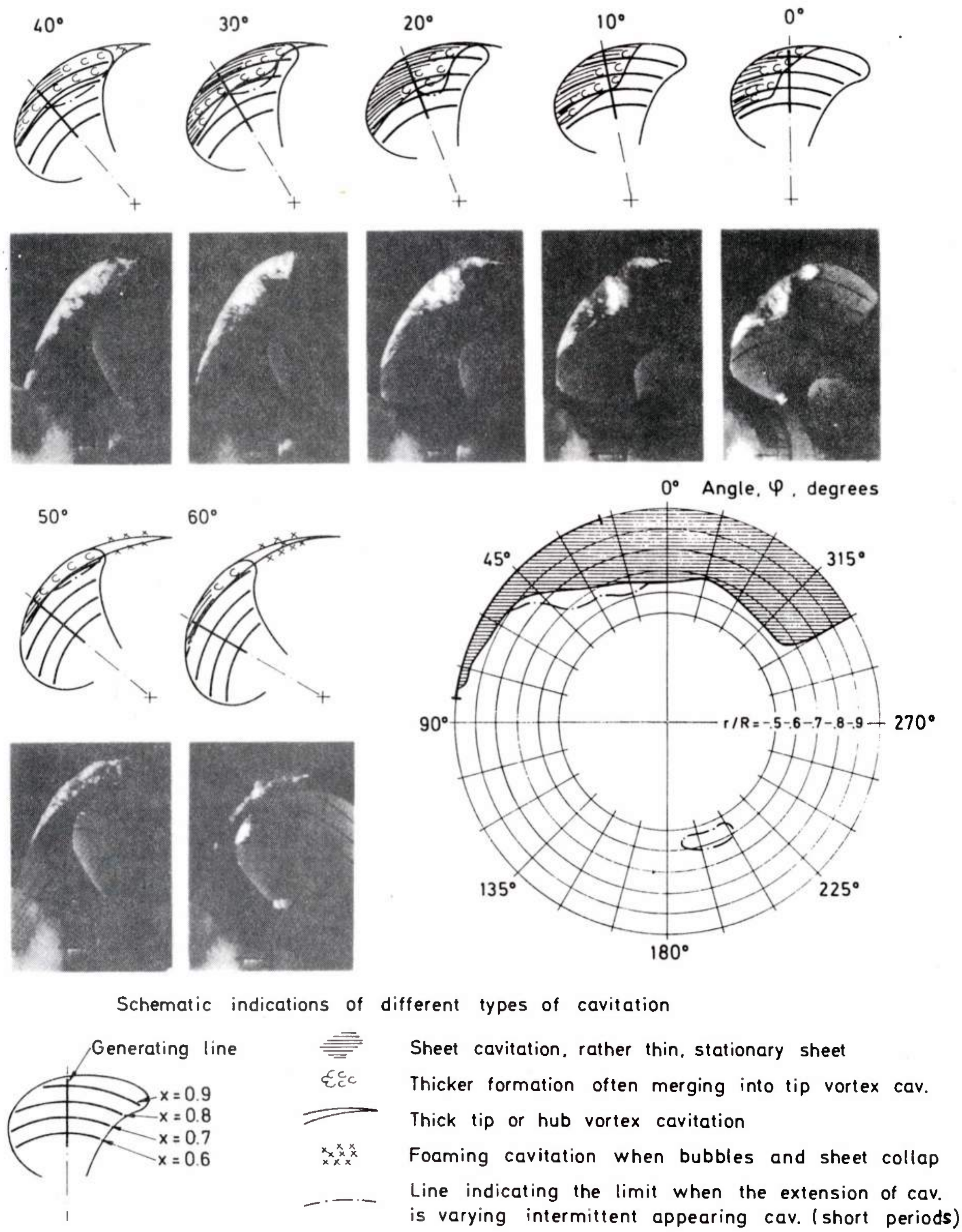


Figure 47 - Propeller Cavitation Extension and Character, along with Schematics of Various Types of Cavitation

(From Lindgren and Bjärne[13])

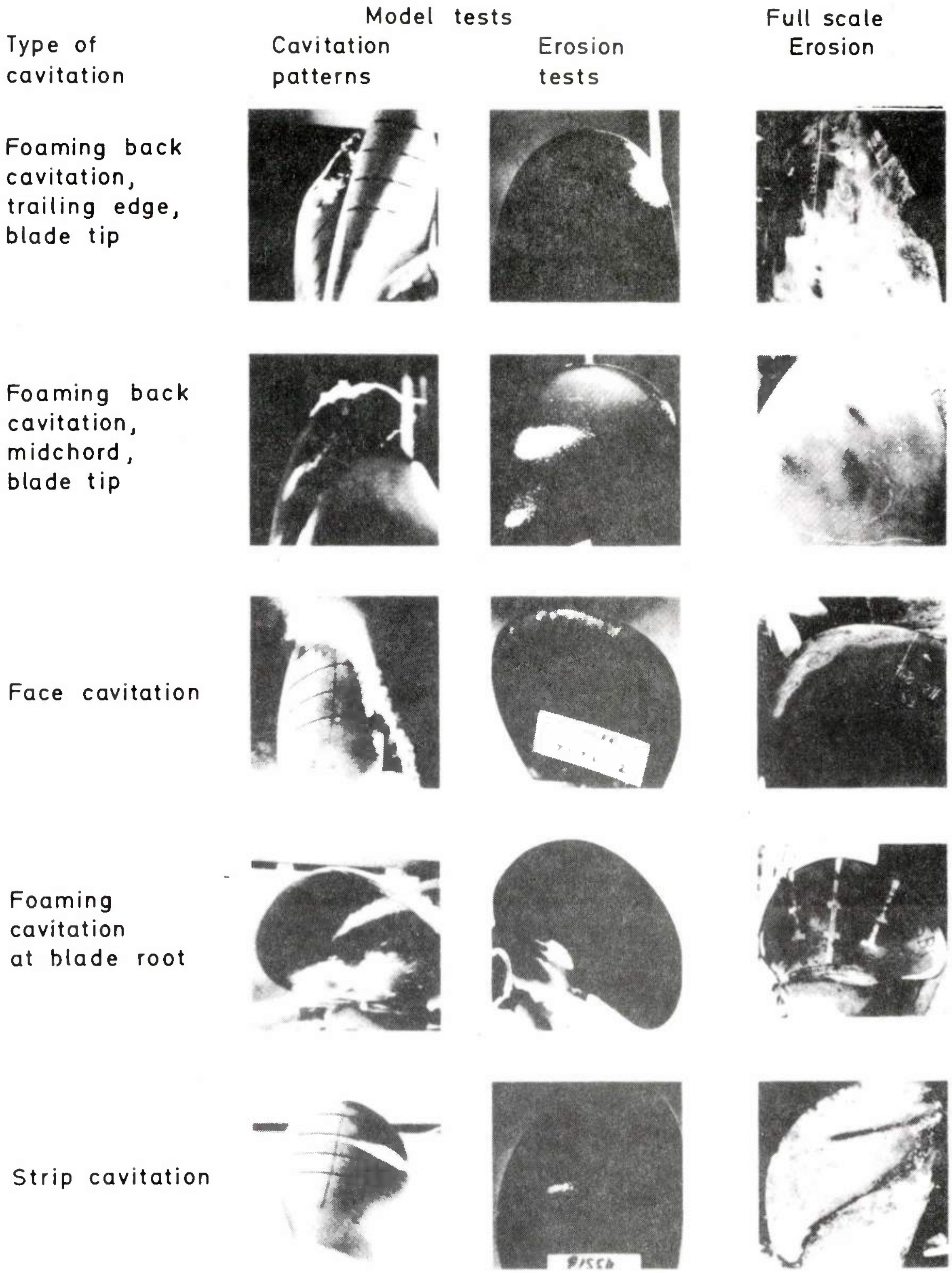


Figure 48 - Examples of Eroding Cavitation
(From Lindgren and Bjärne[13])

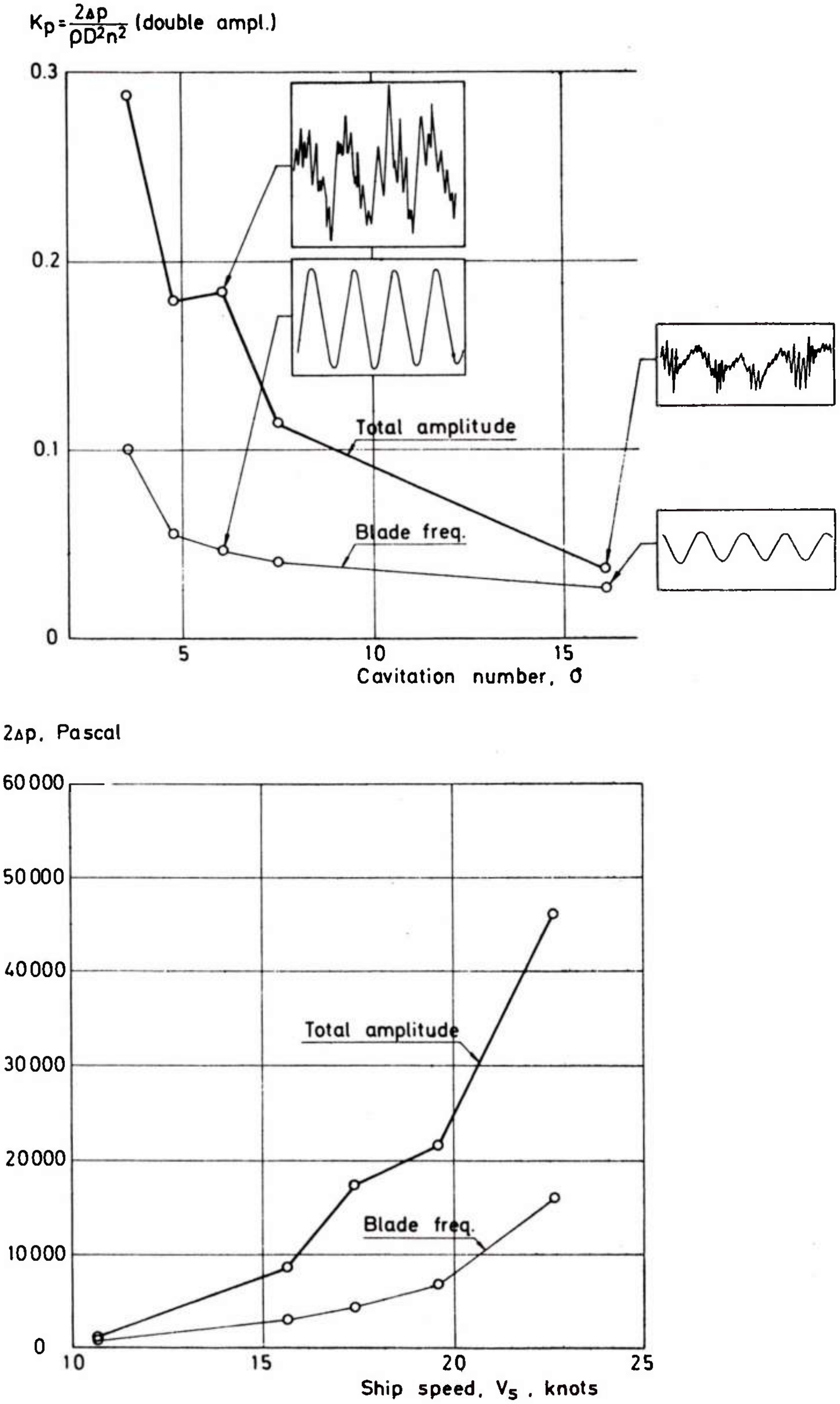


Figure 49 - Pressure Pulse Measurements, Results and Recordings (From Lindgren and Bjärne[13])

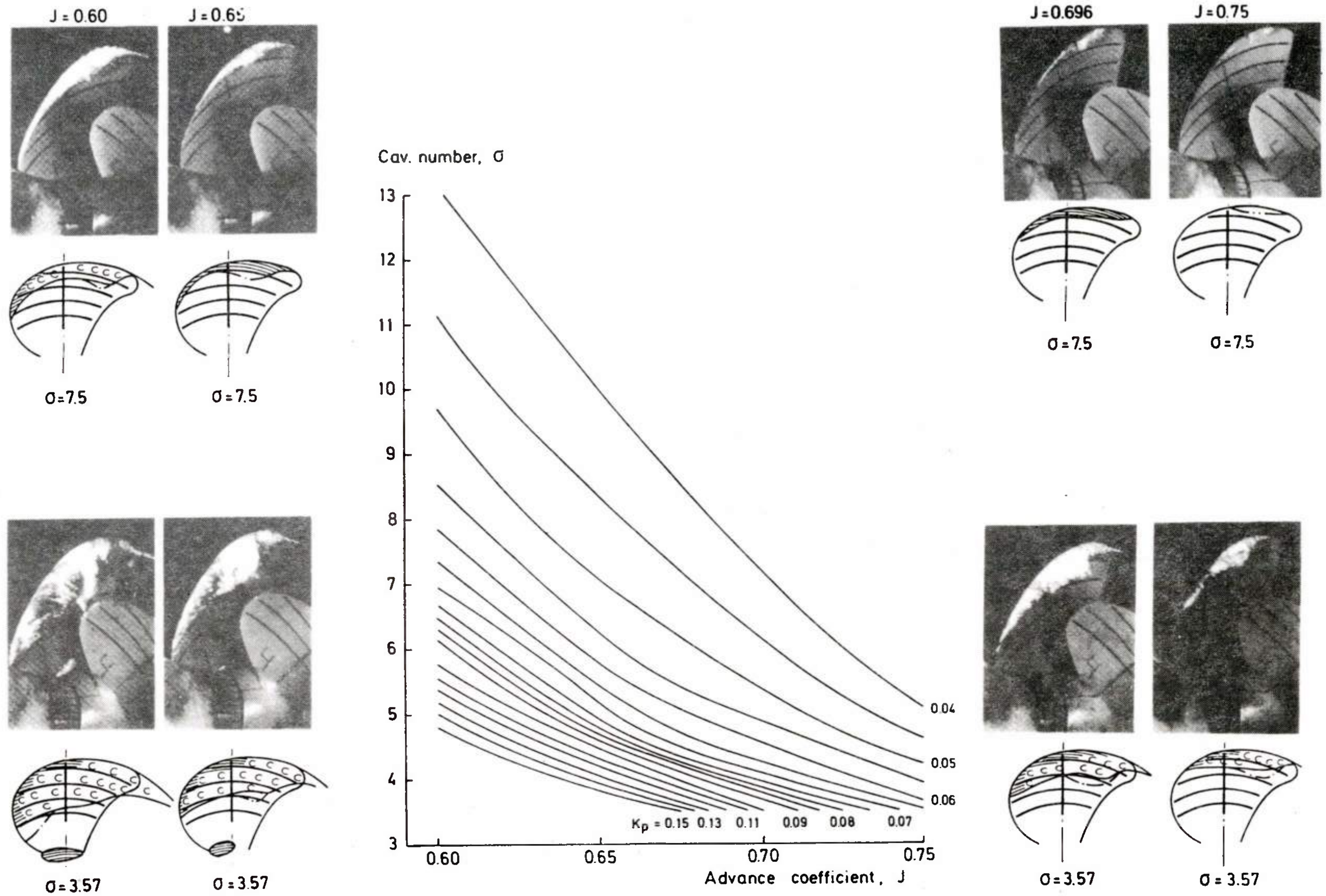


Figure 50 - Influence of Propeller Loading on Pressure Pulse Coefficient and Cavitation Patterns

(From Lindgren and Bjärne[13])

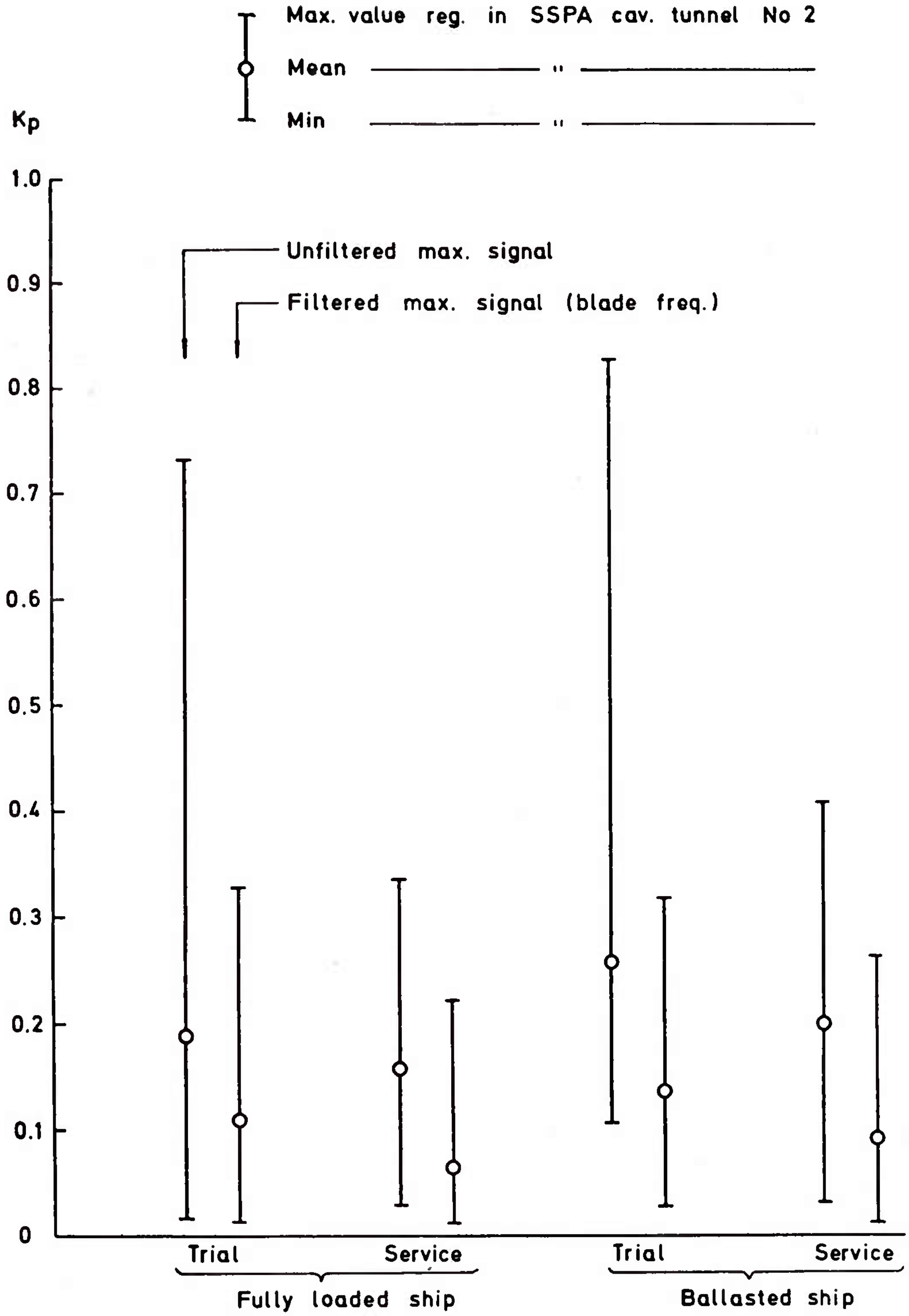


Figure 51 - Results of Pressure Pulse Measurements
(From Lindgren and Bjärne[13])

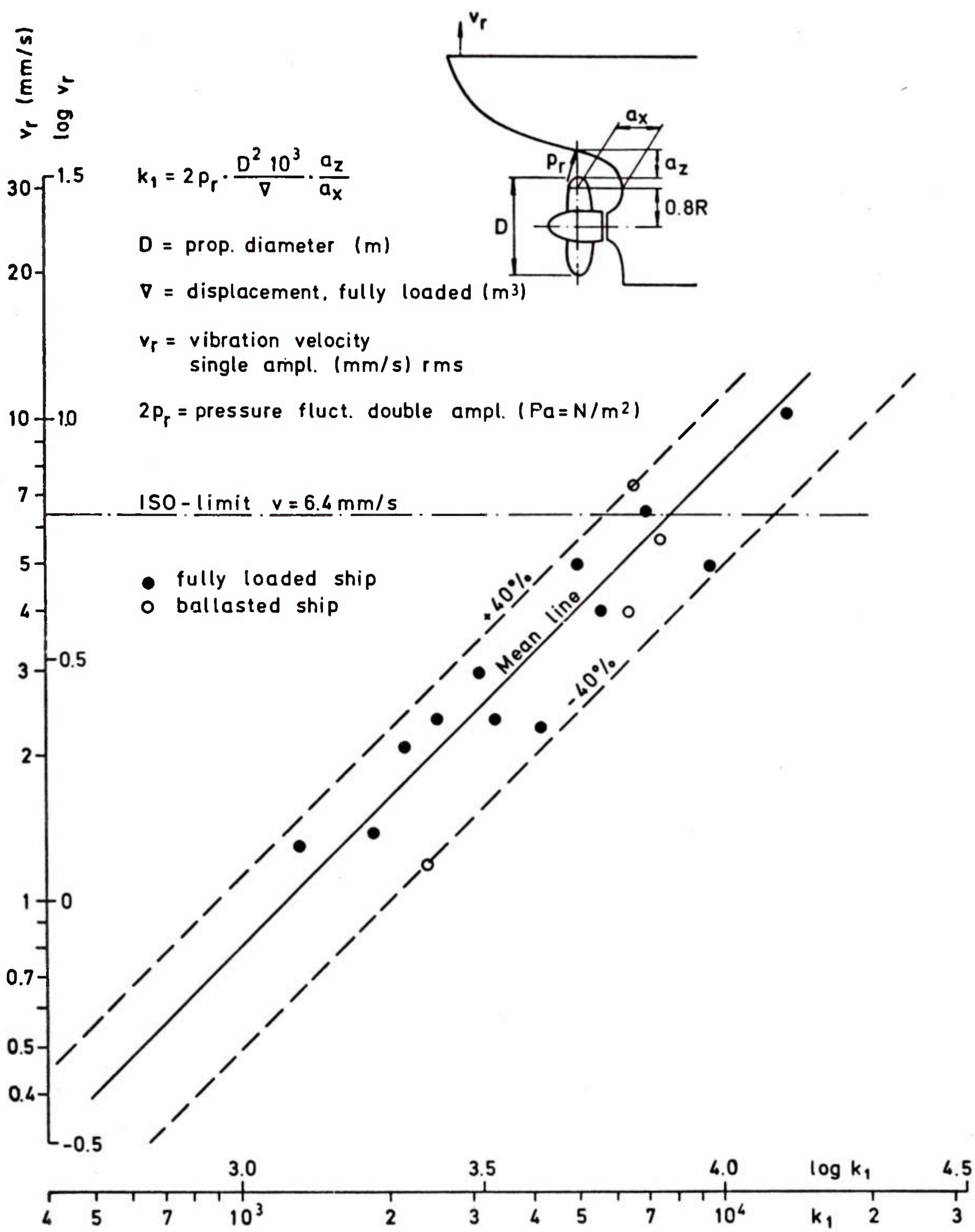


Figure 52 - Pressure Pulse-Vibration Criteria
(From Lindgren and Bjärne[13])

The flow patterns are studied with air bubbles introduced into the water from outlets on the surface of the rear part of the model. The paths of the bubbles indicate the flow lines, which are recorded on photographs. This type of test requires enough water velocity that the bubble motion is not too much effected by displacement forces. Also, tufts of cotton thread are used for flow observances. The tufts are fixed to strings normal to the hull surface, one close to and one 50 mm out from the hull surface in order to permit studies of the 3-dimensional flow pattern. To investigate the stability of the flow a film is made. The purpose of the flow tests is to indicate the possible occurrence of instable and separated flow, which must be avoided, at least in the propeller region.

Correlation, Criteria, and Statistics

With the increase in power, fullness and aft beam of ships, the conditions for the propeller have become worse from the cavitation point of view. Consequently, the risks of the appearance of all kinds of disadvantages caused by propeller cavitation, i.e., erosion, vibration, noise, and efficiency reduction, have increased.

Thus, predicting the cavitation performance of a ship by model tests in the cavitation tunnel has become more and more important. To reliability evaluate model test results, studies of the correlation with full scale are necessary.

Statistics from the model test results and the corresponding geometric properties of propeller and hull are of great value for comparisons and studies of how various parameters influence cavitation.

Criteria for determining limits for acceptable levels of various quantities influencing the cavitation have also been developed with the aid of results from ship model correlation investigations, theoretical considerations, and statistical material (Figure 53).

Full scale observations of cavitation patterns were carried out on a 5000 tdw tanker as long ago as in 1961 by SSPA. These were the first studies of their kind on big merchant ships. The agreement between model and full scale has been found to be good. In order to stabilize the propeller turbulence, stimulating nets are now usually fitted on the ship model in front of the propeller aperture. These nets do not influence the velocity distribution, but they increase the degree of turbulence in the flow. Moreover, the propeller model nowadays is always coated with a heatproof paint to produce a surface roughness better corresponding to full scale conditions.

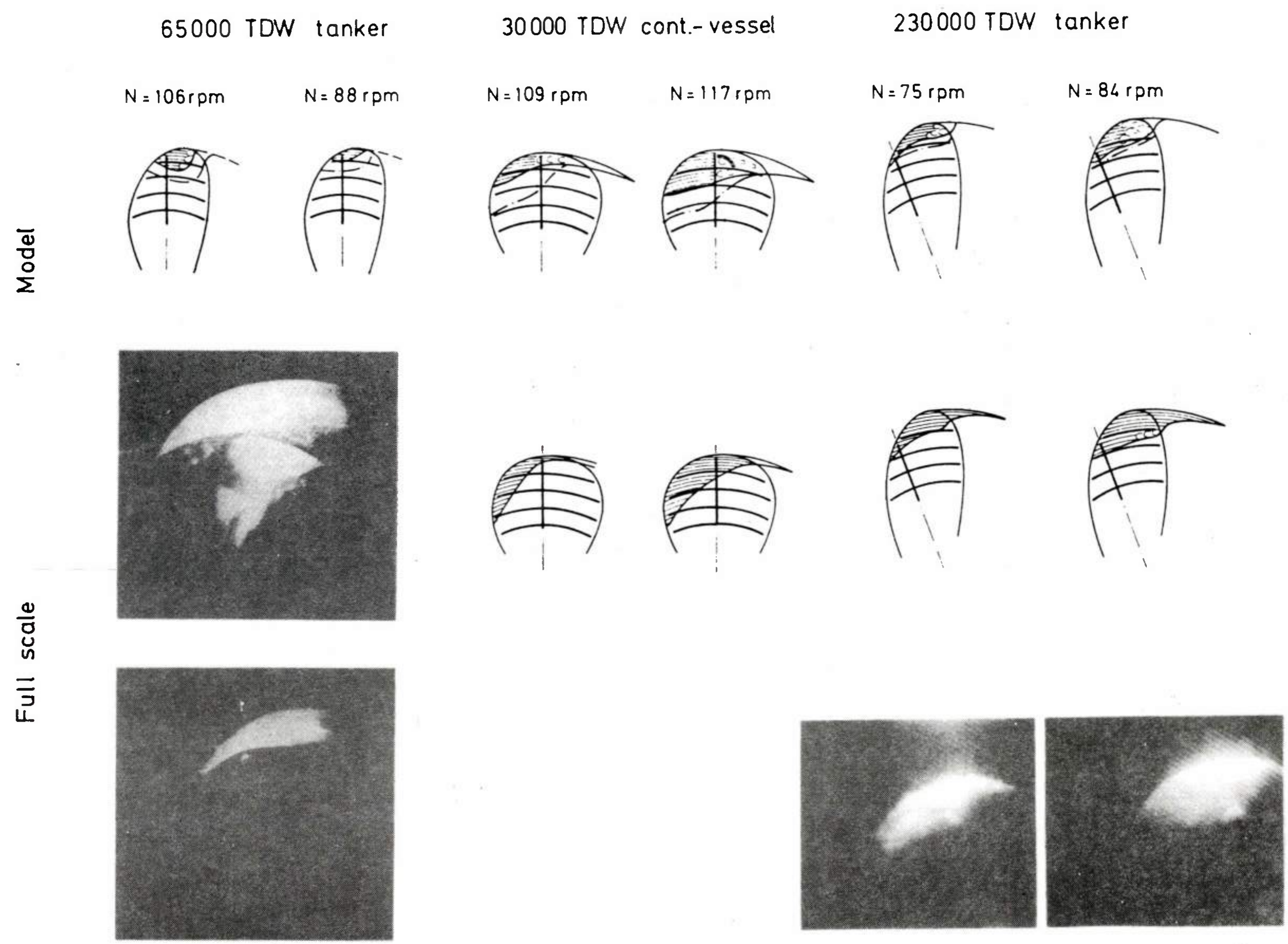


Figure 53 - Results from Ship Model Correlation Investigations of Cavitation Patterns
(From Lindgren and Bjärne[13])

Cavitation erosion noticed on ship propellers has for many projects been compared with the corresponding results of the paint tests described above. The model experiments have usually been carried out after the full scale erosion has been observed, since no propeller with a tendency to erode during model tests is nowadays regarded as acceptable (Figure 54). A criterion for required propeller blade area in different velocity distributions was estimated on the basis of statistics of erosion tests and full scale observations. Of course other geometric parameters do influence the possibilities of erosion and these are being studied further.

The pressure pulses measured on the ship model hull surface have, for a great number of projects, been compared with the corresponding full scale values. Usually good agreement between model and full scale results is obtained at least with regard to blade frequency pulses (Figure 55). About 100 projects have been examined in the large tunnel with regard to pressure pulses. Interestingly, one of the worst cases and one of the best are ships of the same type with identical dimensions but different afterbody shape; conventional and open stern, respectively (Figure 56).

The relation between the pressure pulses and the corresponding vibration velocities measured in full scale has been studied. The size of the ship as well as the relation between vertical and horizontal propeller clearances have been taken into consideration (Figure 57). Obviously large ships can withstand higher pressure pulses than small vessels, due to stiffer constructions for the former. As an acceptable limit of pressure pulses, the level of velocity according to ISO (International Organization for Standardization) is used (Figure 52).

The above studies have shown that afterbody shape should be carefully examined from the vibration aspect before it is finally selected. Very often, however, the form is determined before the cavitation test takes place. The remaining modes of improvement are then the application of afterbody fins and/or a redesign of the propeller (Figure 58). Afterbody fins are applied to increase the water velocity in the upper part of the stern and thus to partly reduce the corresponding wake peak in the propeller plane. For full ship forms, rather small and simply formed stern fins are adequate, but for more slender ships, large and more curved fins must be used.

If acceptable pressure pulses cannot be achieved by other means, the propeller must be redesigned. A reduction of the blade tip loading by the choice of a

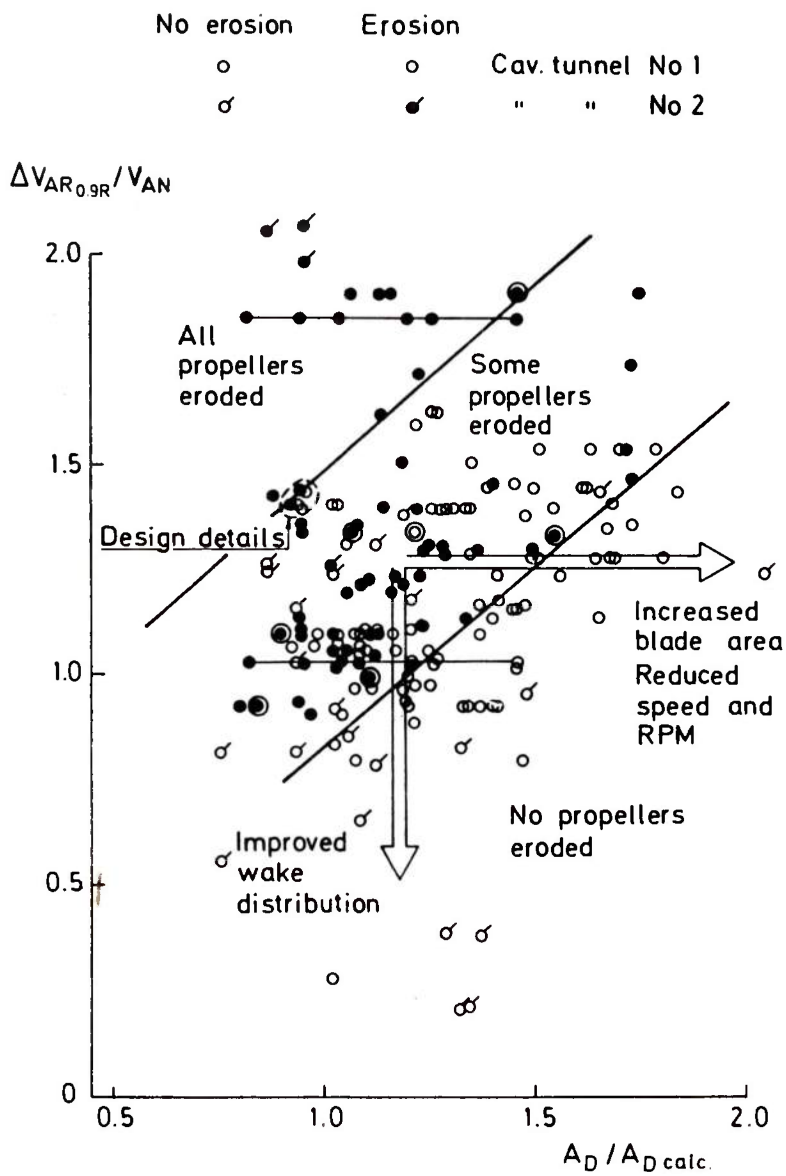


Figure 54 - Results from Ship Model Propeller Erosion Tests
(From Lindgren and Bjärne[13])

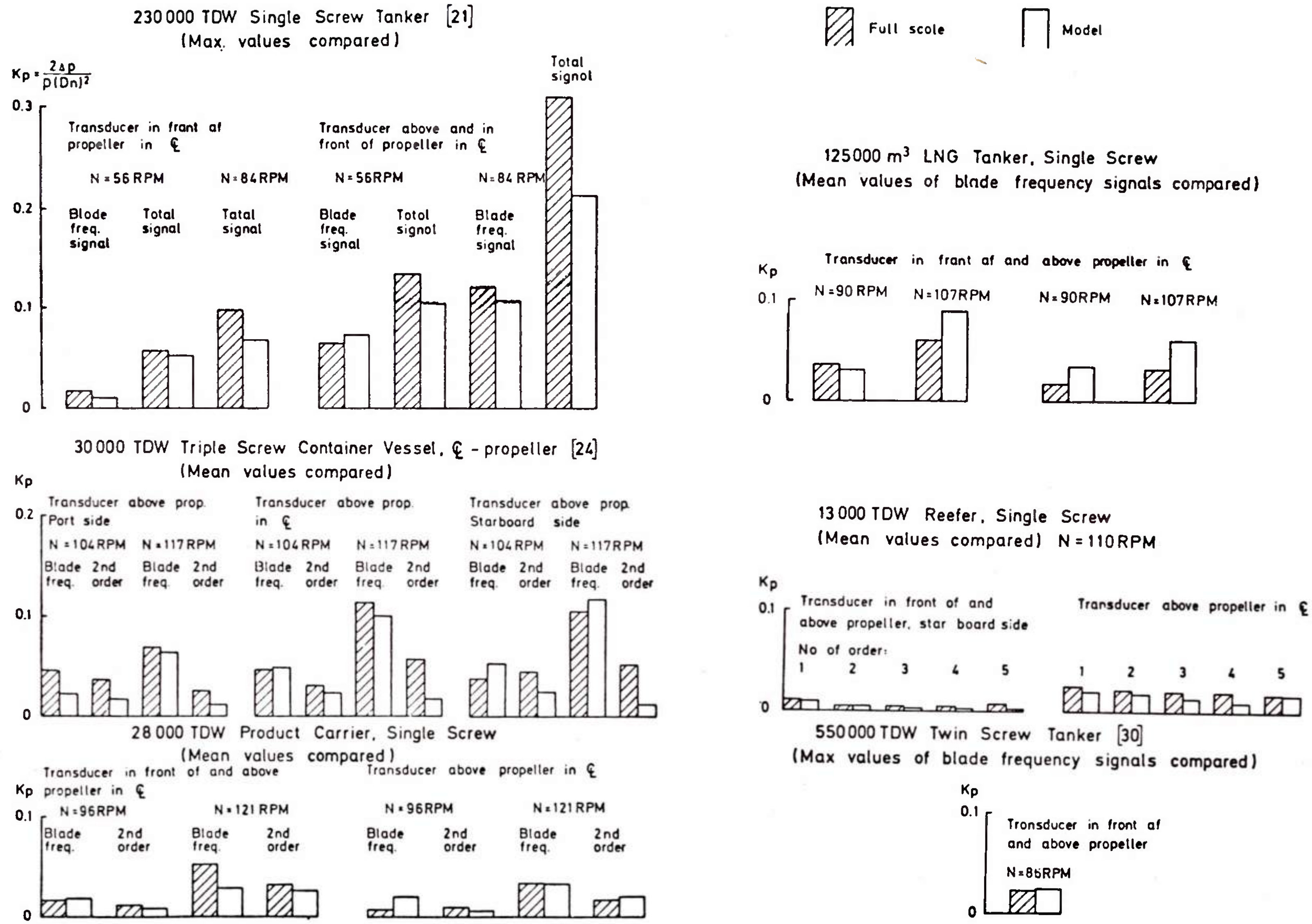


Figure 55 - Comparison of Pressure Pulses Measured on Model and Full Scale Hulls

(From Lindgren and Bjärne[13])

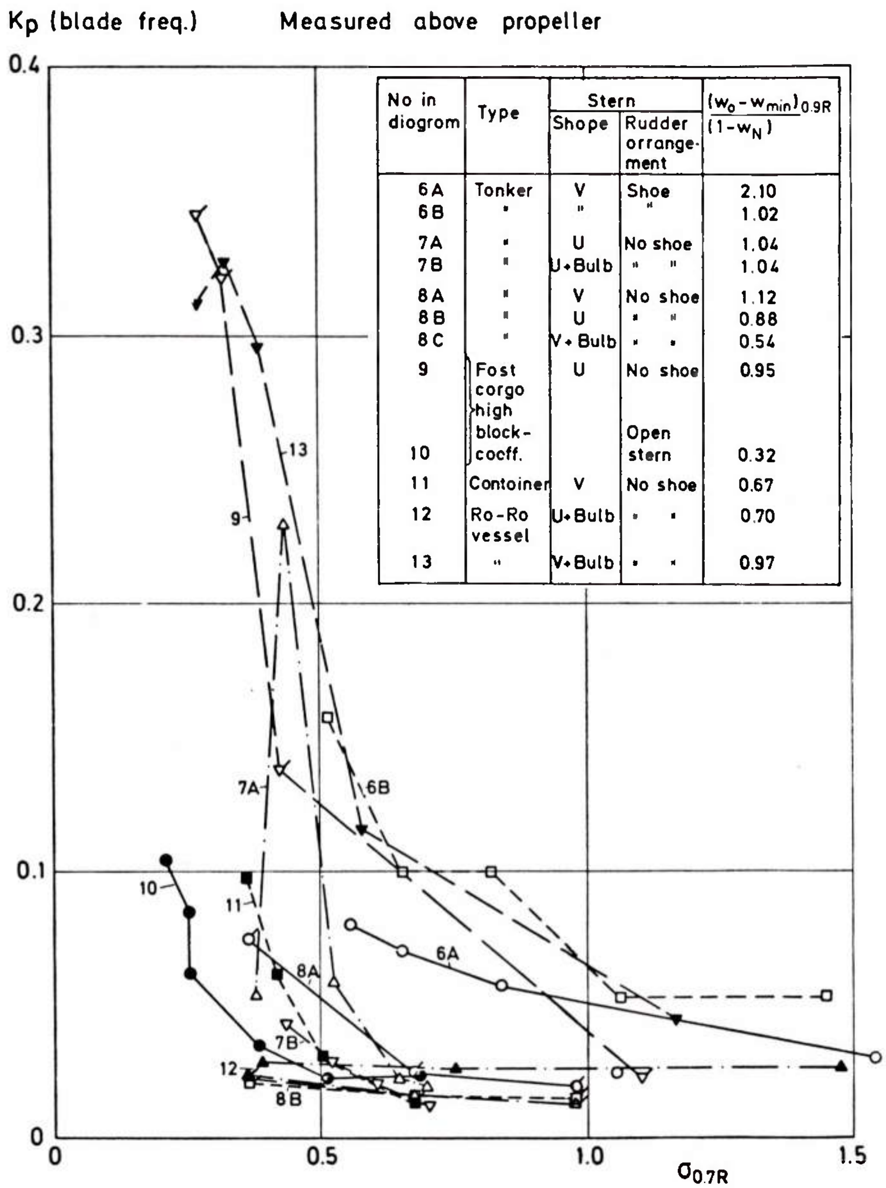


Figure 56 - Pressure Pulse Coefficients for Some Different Projects
(From Lindgren and Bjärne[13])

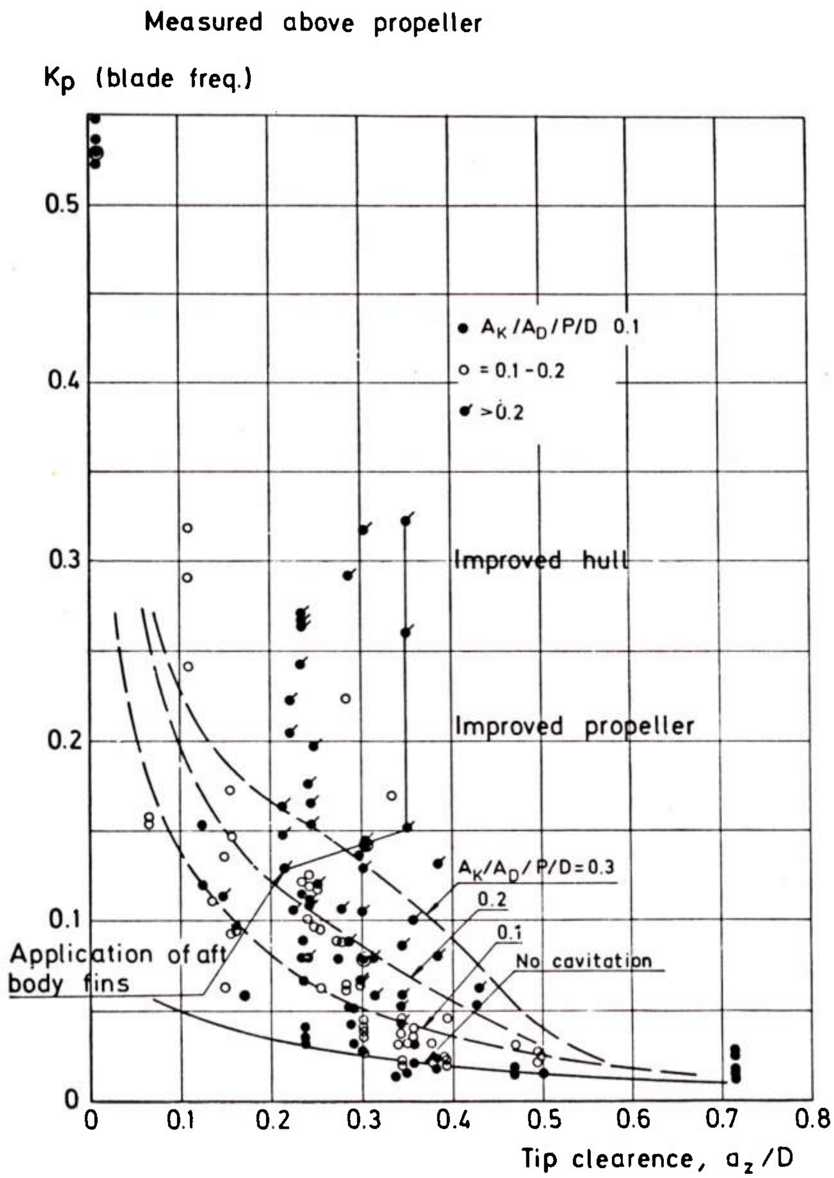


Figure 57 - Pressure Pulse Coefficients, Influence of Propeller Clearance (From Lindgren and Bjärne[13])

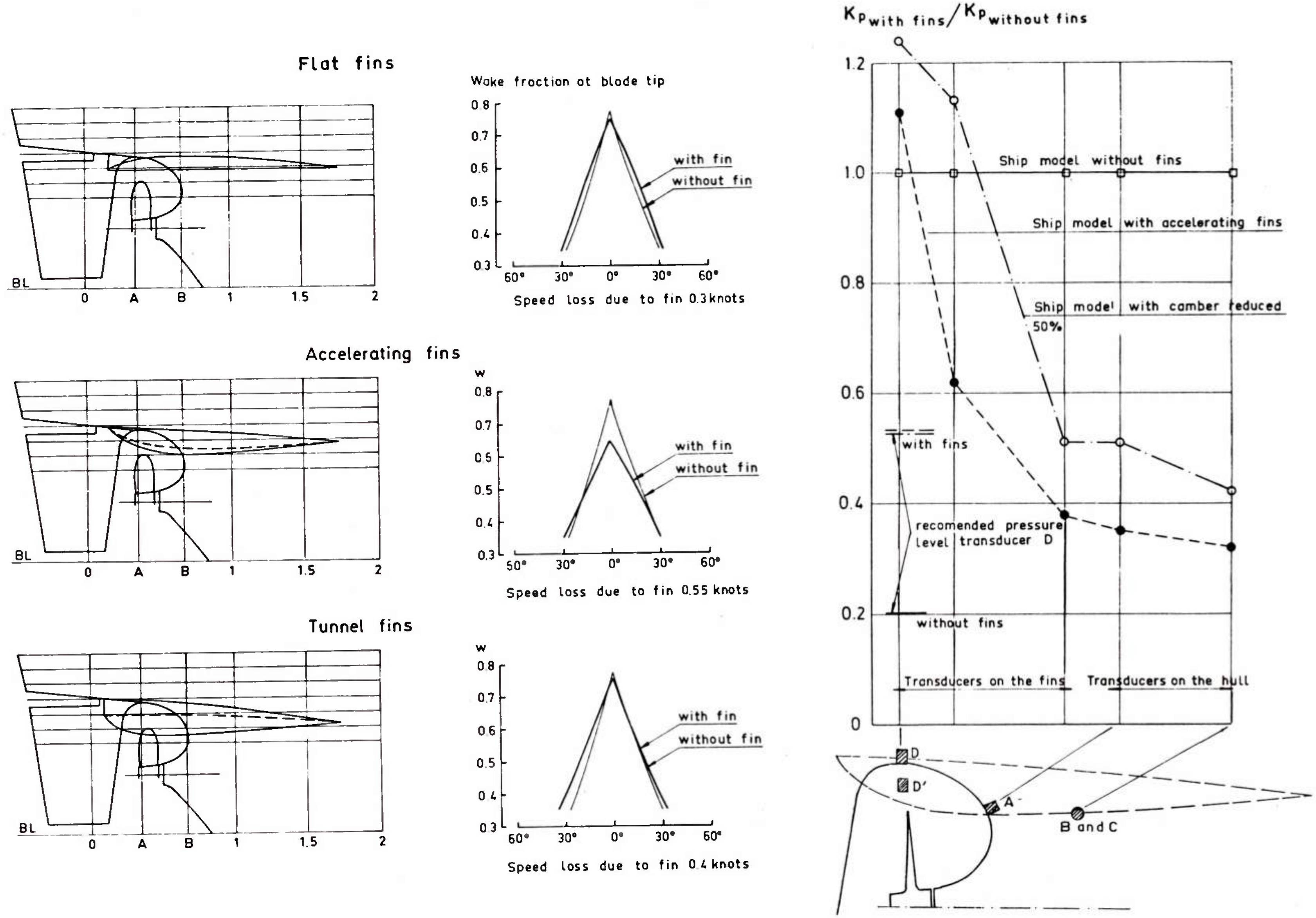


Figure 58 - Influence of Aft Body Fins on Wake, Speed and Pressure Pulses
(From Lindgren and Bjärne[13])

suitable radial circulation distribution has reduced pressure pulses. The change reduces propeller efficiency, but the corresponding power increase is partly offset by improved hull and relative-rotative efficiency. An increased skew can also be introduced (Figure 59).

Recently, a rather extensive investigation was carried out in the large test section of cavitation tunnel 2 at SSPA. The aim of the study was to see how the compromise between efficiency, cavitation erosion, and vibration excitation properties of a propeller design is affected in a particular case when design parameters are varied. The investigation was carried out for a loading case corresponding to a RO/RO ship. Blade form and radial load distribution were varied systematically (Figure 60). The test results giving influence on efficiency and pressure fluctuations are shown in Figure 61.

Future Development

The large test section of the large cavitation tunnel has been modified by the installation of fairings so that the section area is decreased to 2.6 m × 1.15 m (from 2.6 m × 1.5 m). The water speed is thereby increased to 8.8 m/s (from 6.8 m/s) (Figure 62). This modified test section has been used primarily for tests with high speed crafts. The experience with this section is so favorable that a completely new test section will probably be designed and constructed for testing high speed crafts. The main part of the two last chapters above has been taken from: SSPA Publication No. 86,[13] 1980, "Ten Years of Research in the SSPA Large Cavitation Tunnel," by Hans Lindgren and Eric Bjärne. This publication may be referred to for further details The results from the RO/RO ship investigation has been published in Nordforsk, Miljövårdsserien 1981/2[14]: Noise Sources in Ships, 1 Propellers, Paper H: "Propeller Parameter Studies," by C.A. Johnsson. Also in this case, a more detailed study is recommended.

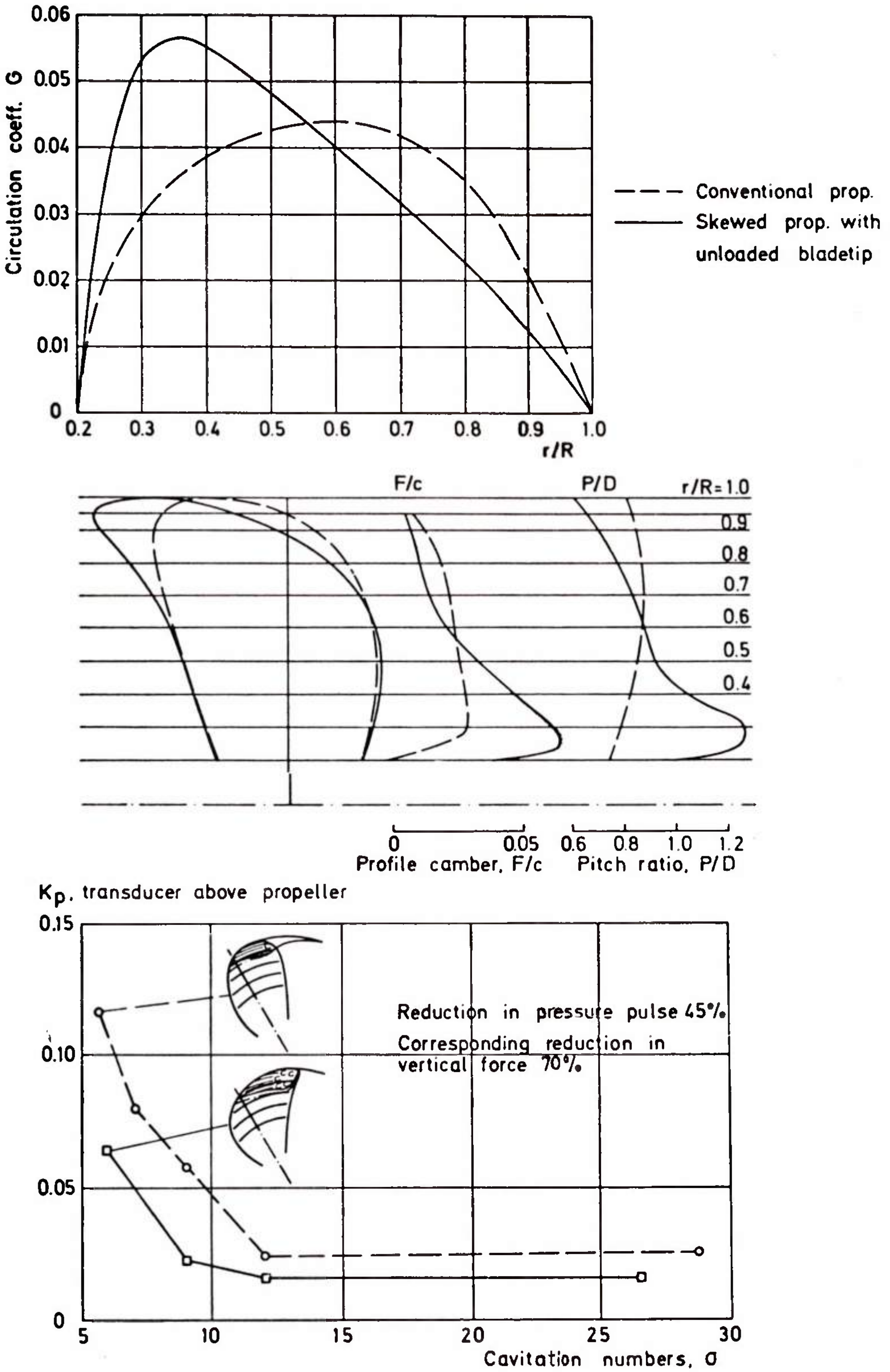


Figure 59 - Influence of Propeller Design on Cavitation Patterns and Pressure Pulses

(From Lindgren and Bjärne[13])

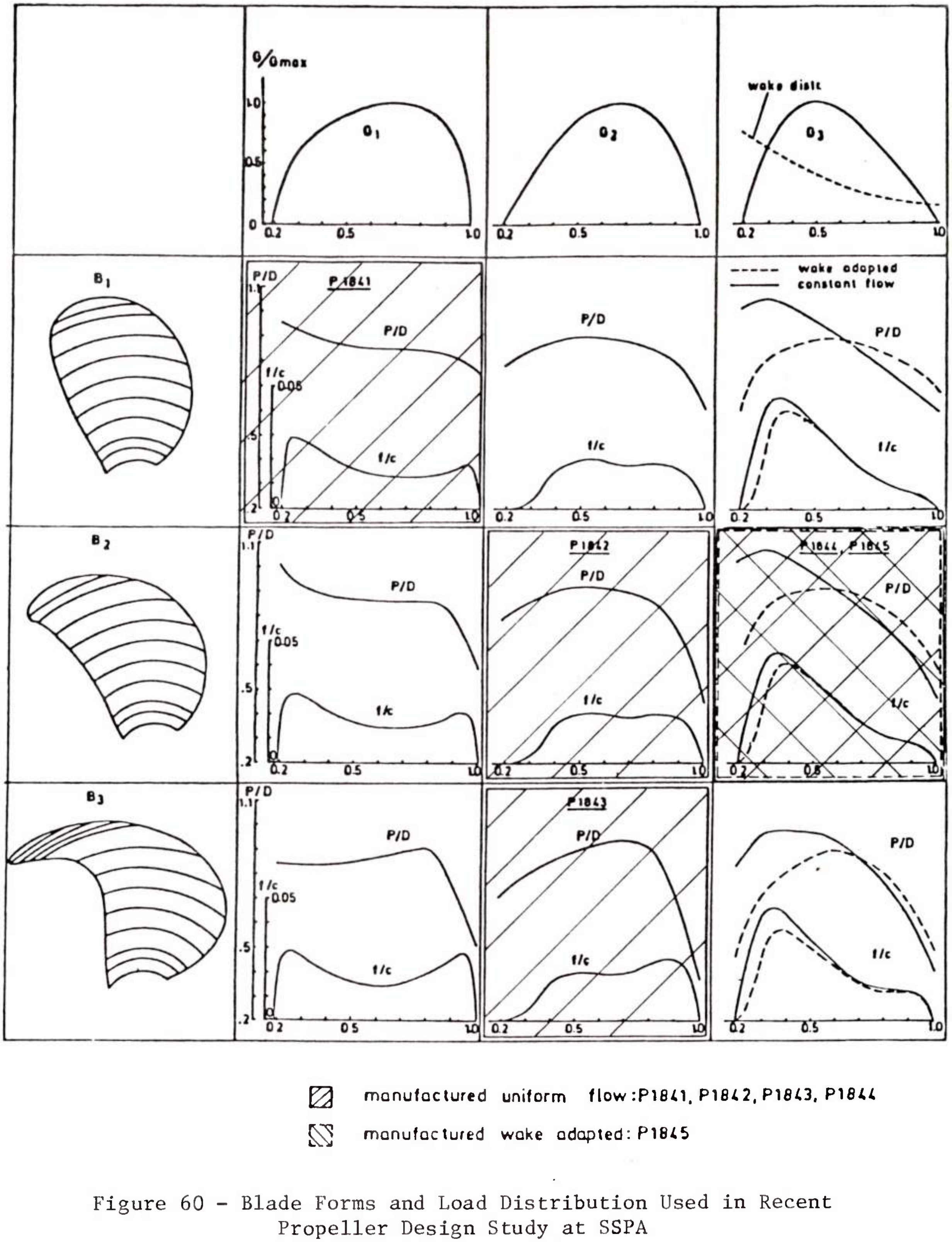


Figure 60 - Blade Forms and Load Distribution Used in Recent Propeller Design Study at SSPA
(From Johnsson[14])

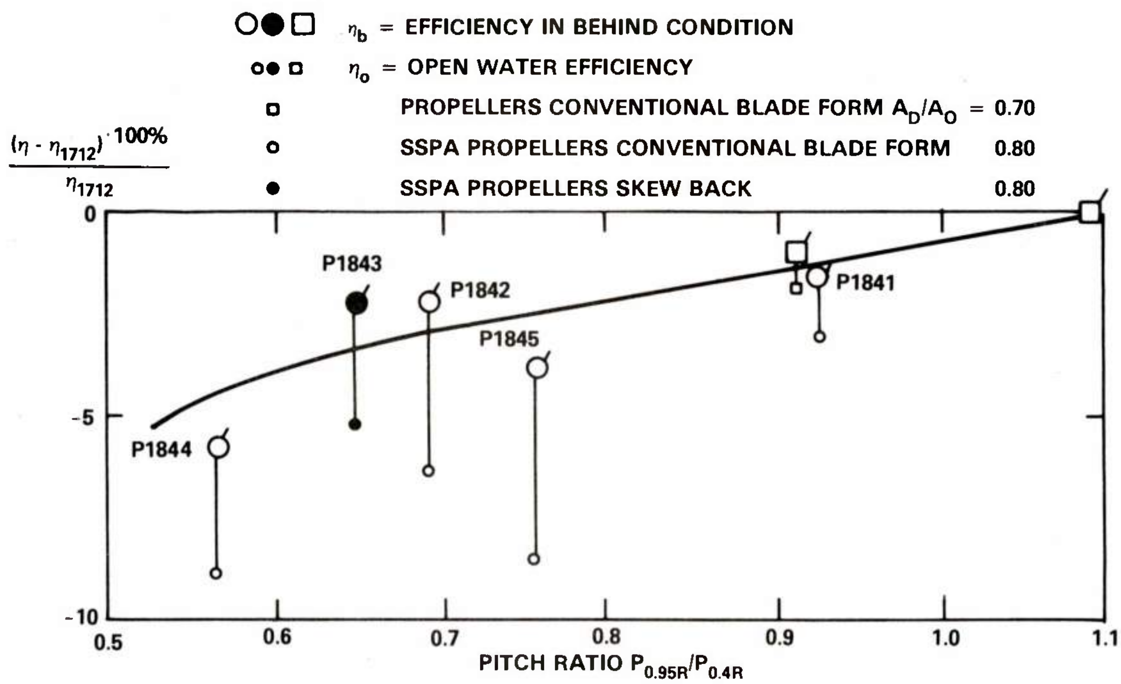


Figure 61a - Influence of Tip Loading and Skew on Efficiency

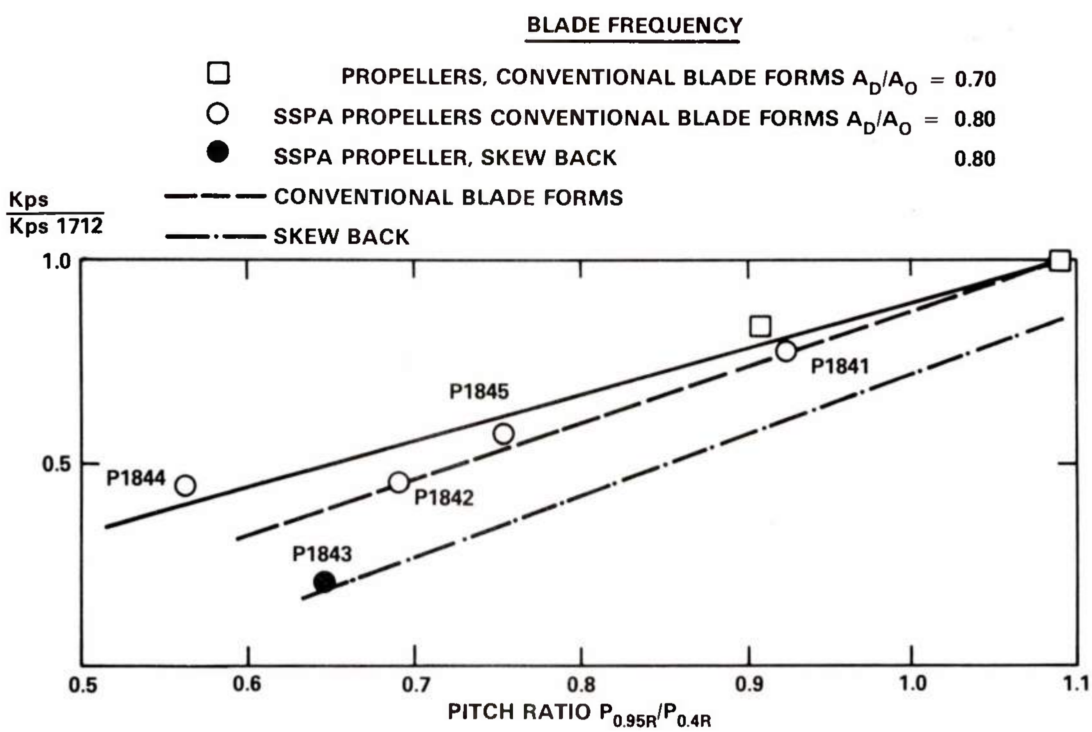


Figure 61b - Influence of Tip Unloading and Skew on Pressure Fluctuations

Figure 61 - Efficiency and Pressure Fluctuation Results
(From Johnsson[14])

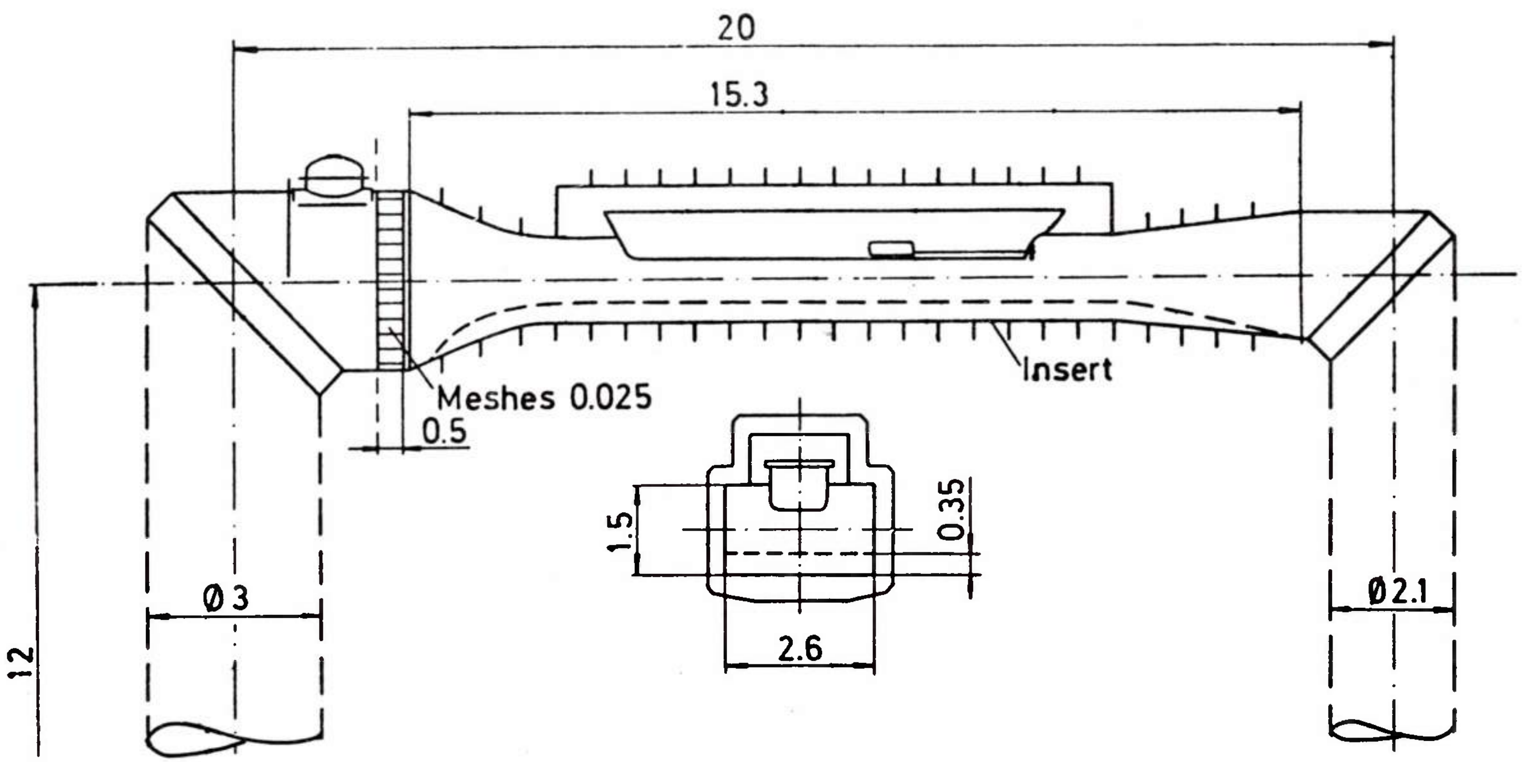


Figure 62 - Large Cavitation Tunnel with Complete Ship Model

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